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THE PALEOLIMNOLOGY OF TWO SHALLOW LAKES IN CENTRAL ALBERTA

by

(C) JOHN RODERICK FORBES

A THESIS

SUBMITTED TO THE FACULTY OF GRADUATE STUDIES AND RESEARCH

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The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research, for acceptance, a thesis entitled:

The Paleolimnology of Two Shallow Lakes in Central Alberta

submitted by: John Roderick Forbes

in partial fulfilment of the requirements for the degree of Master of Science in Limnology.

ABSTRACT

An interpretation of postglacial change in water quality and productivity has been made for two shallow, productive lakes in central Alberta.

Pollen analysis suggests that in the earliest part of the record, approximately 5600 BP, the vegetation around Lac Ste. Anne (53° 42' N, 114° 21' W) was more typically parkland and the climate slightly drier than at present. Erosion rates have remained more or less constant, so any climatic shift has not been pronounced.

Productivity in Lac Ste. Anne has changed very little, although there is some evidence that macrophytes made a greater contribution to total production during the early part of its history.

Hastings Lake (53° 30' N, 113° 00' W) has been more sensitive to changes in the balance of precipitation and evaporation. From approximately 4800 to 3500 BP the lake appears to have been considerably shallower than more recently. Productivity during this early phase was considerably less than later. Macrophytes and allochthonous organic matter in the form of leaf litter contributed a greater proportion of the organic influx. Following the rise in water levels productivity rose and remained fairly steady until about 2500 BP, when a slight decline occurred. Throughout the high water phase oxygen depletion has never been a serious problem. Any period of reducing conditions in the surface sediments has probably been brief.

The data suggest that productivity in the lakes has never been nutrient - limited. Elevation of the lake surface appears to increase potential volume for production and reduce turbulent resuspension of

bottom sediments, permitting greater light penetration and enhanced algal production.

In terms of climatic history, the record conforms to evidence from other studies. It supports interpretations of the Hypsithermal Period of warm and dry conditions occurring in Alberta.

The differences between the sediments of Lac Ste. Anne and the two basins of Hastings Lake demonstrate the strongly individual response of basins and lakes to climatic events.

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THE PALEOLIMNOLOGY OF TWO SHALLOW LAKES IN CENTRAL ALBERTA

INTRODUCTION

The majority of lakes in the prairie parkland and associated ecotones are shallow, rich in nutrients and highly productive (Hickman 1978, Hickman and Jenkerson 1978). This study focuses on two such lakes in central Alberta: Hastings Lake (53° 30' N, 113° 00' W) and Lac Ste. Anne (53° 42' N, 114° 21' W). An interpretation of postglacial change in water quality and productivity is made, based upon an analysis of organic and inorganic constituents of sediment cores. Evidence of changes in environmental conditions of the watersheds is also discussed.

The paleolimnology of these lakes contributes to the general reconstruction of postglacial climatic events of the region. Due to the difficulties of interpretation, shallow, non-stratifying lakes have received scant attention from paleolimnologists. However, useful information may be extracted from their sediments. An important part of this study is an assessment of the resolution possible in cores from such lakes. Within the limits of this resolution the historical reconstruction is made.

The water quality of a number of central Alberta lakes has allegedly declined during this century (Anonymous 1977). The paleo-environmental interpretation made here reveals the range of water quality conditions they have passed through, contributes to an under-standing of the factors controlling productivity within them, and should assist in predicting the ramifications of any management policies.

APPROACHES TO PALEOLIMNOLOGY

Numerous indicators have been used to interpret the history of lakes. These may be broadly classified as physical, chemical and paleontological.

An important requirement in any investigation is chronological control. Although stratigraphic analysis, particularly the use of indicator fossils such as pollen (Faegri and Iversen 1975), has long been employed, radiocarbon dating is now established as the major technique for dating Quaternary sediments. A number of problems are associated with this. Suess (1970) has calibrated the radiocarbon time-scale against dendrochronologically dated samples of Bristlecone Pine to correct for drift in the ^{14}C content of atmospheric CO_2. Carbon isotope fractionation during photosynthesis may lead to modified ratios of carbon isotopes deposited in the sediments, resulting in anomolous dates on this material (Fritz and Poplawski 1974). Studies of very recent events have used peaks of radioactive isotopes such as cesium-137, produced by atmospheric testing of nuclear weapons, as chronological flags (Pennington 1973).

Geological evidence of a physical nature for lake history is primarily in the form of stratigraphic information. Where annual laminations occur they provide an especially sensitive record of depositional history (Renberg 1976). Raised beaches (Richardson 1969) and elevated lacustrine clays, together with topography (Langford 1977) have been used as evidence of fluctuations in lake levels.

Chemical and fossil evidence are generally more useful in establishing the history of biological events. The work of Mackereth

(1966) was fundamental in consolidating quantitative analysis of organic and inorganic elements for environmental reconstruction. His careful review of the factors controlling the influx of these components to the the sediments has been the basis of many interpretations. Other studies have concentrated on the behaviour of specific elements, with phosphorus, iron and manganese being of particular concern (Bortleson and Lee 1974, Osburne and Moss 1977). Phosphorus is generally implicated as the most critical nutrient in the control of primary production in lakes (Schindler 1977). Phosphate has a strong tendency to coprecipitate with iron and manganese. Its availability is strongly influenced by the redox conditions of its environment, of which iron and manganese are sensitive indicators (Mackereth 1966). The work of Viner (1977) on the sediments of Lake George, Uganda, is of special relevance for its concern with the behaviour of chemical features in a non-stratifying lake, where the bottom is subject to frequent turbulent disturbance. His interpretation of the depth of disturbance was based upon the concentration of orthophosphate and ammonia-nitrogen in the upper part of the cores.

Isotope ratios are of value in a number of ways. The ratio of oxygen-18 to oxygen-16 in fossil shells provides a tool for paleotemperature studies (Fritz and Poplawski 1974). Stiller (1976) has used the stable isotope composition of allochthonous and autochthonous calcium carbonate and organic matter to estimate the relative contributions of these components to recent sediments. The technique was more useful for interpreting the source of carbonates than of organic matter.

The use of biochemical fossils, notably plant pigments and their degradation products, has received much attention. As direct products of plant production they may act as sensitive indicators of

trophic history. Vallentyne (1955) was the first to use sedimentary pigments for a comprehensive paleolimnological reconstruction, although some recognition of their preservation was recognized earlier (Brongersma-Sanders 1951). Sanger and Gorham (1970, 1972) have refined his work and made an important contribution to the comparative diagenesis of terrestrial and aquatic pigments. In particular they explored the relationship of pigment diversity and the ratio of chlorophyll derivatives to carotenoids as indicators of the nature of the source material. Detailed chromatographic analysis by Brown and his coworkers (Brown et al. 1977, Daley et al. 1977) has delineated many of the diagenetic pathways followed by chlorophylls in lake waters and sediments. This work has shown that some degree of caution must be employed for detailed interpretations of productivity based upon undifferentiated pigment extractions.

Pollen analysis is an ancient and respected art in paleoecology (von Post 1918). Though rarely directly applicable to paleolimnology, except where there is a significant component of aquatic macrophyte pollen, it does provide a framework of regional climatic history and a record of vegetation changes in the watershed. Ritchie (1976) has reviewed the late Quaternary history of vegetation in the western interior of Canada, while shifts in the boreal forest-tundra ecotone in Mackenzie and Keewatin, Northwest Territories, have been investigated by Nichols (1975).

Sub-fossil algal remains, primarily diatom frustules, are a major tool. Their analysis is most commonly applied to interpretations of trophic status (Crabtree 1969) or changes in community structure (Osburne and Moss 1977), but may be used in a more restricted application as indicators of such factors as pH (Merilainen 1967).

The problem of the validity of sedimentary records as a reflection of real events in the water above is significant. One approach is a comprehensive study of production and water chemistry, with simultaneous recording of influx of elements to the sediments. Studies of this nature have been carried out by Wetzel (1970) on a marl lake in Michigan and by Gorham et al. (1974) on the English Lakes. Considering a more restricted problem, Håkanson (1977) has determined the zones of erosion, transportation and deposition of sediment based upon its water content. In general surface sediments with a water content greater than 75% are in zones of accumulation. The horizontal pattern of influx of elements to the sediments is controlled by a number of factors. Among the more important is depth in relation to the metalimnion in stratifying lakes, to which different elements respond in a variety of ways (Ryding and Borg 1976). Basin shape has a strong influence on the sedimentation rate at the centre. Focusing of the sedimentary influx is much more strongly distorted in basins conforming to hyperboloids and frustrums (wedge forms) than in those of ellipsoid or sinusoid form (Lehman 1975). In the latter there is much less direction of early sedimentation to the centre of the basin. However, analysis of surface sediment samples from the centres of several thousands of Saskatchewan lakes has indicated, based upon the relationship between zinc and organic content, that these samples accurately reflected the regional metal contents of surficial sediments and bedrock, where ignition loss in the samples exceeded 12% (Garrett and Hornbrook 1976, Parslow 1977).

As noted above Viner (1977) explored the problem of bottom disturbance. Davis (1968) measured the effect of resuspension of pollen

grains on their final distribution in the sediments. She found that the process reduced variations in the relative percentages of different pollen types, but distorted the total influx of grains at different locations.

DESCRIPTION OF HASTINGS LAKE AND LAC STE. ANNE

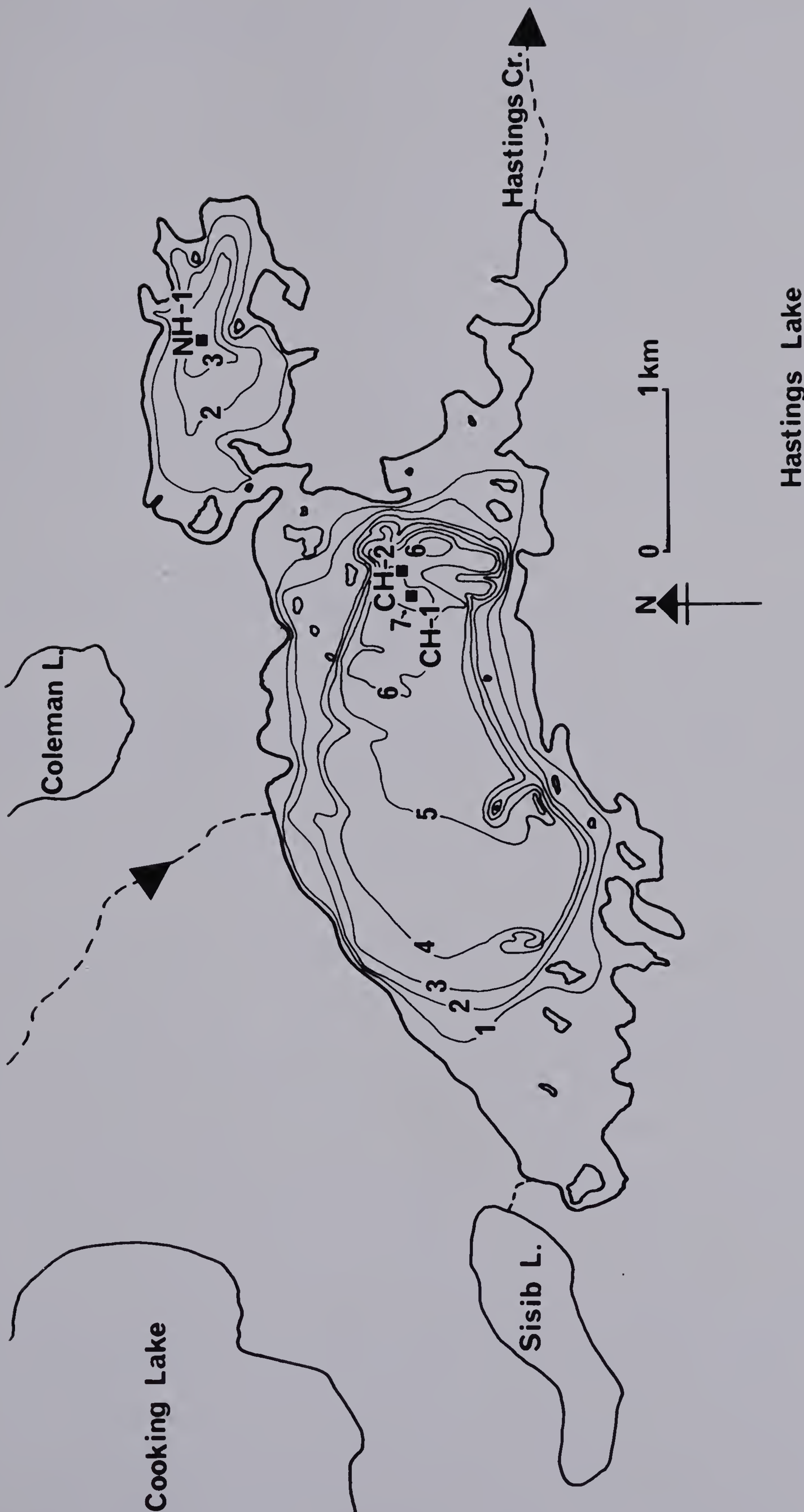
Hastings Lake (fig. 1) lies in the Cooking Lakes moraine some 40 km ESE of the city of Edmonton. The surficial geology of the western portion of the moraine was first mapped by Bayrock and Hughes (1962), while Emerson (1977) has carried out a study specifically of the moraine itself. It is classified as a hummocky disintegration moraine, formed where a portion of the continental ice sheet was detached at the close of the last glaciation and melted in place. The landscape has numerous small basins occupied by shallow lakes, sloughs and temporary ponds. Surface drainage is very poorly developed, with many basins lacking any outlet. Landforms characteristic of stagnant ice decay abound, including knobs, kettles, prairie mounds and linear disintegration ridges (Emerson 1977).

There are two till units that represent separate ice advances. Neither has been dated in the Cooking Lakes area. However in the Fort Assiniboine district, material from above a unit considered equivalent to the lower till of the Cooking Lakes moraine has been dated at 52000 $\pm$ 1760 ^{14}C years BP (St. Onge 1972a). This suggests that the lower till unit was deposited during early Wisconsin time. Molluscan shell remains recovered from superglacial lacustrine sediments on the upper till have been dated between 10900 $\pm$ 190 and 9050 $\pm$ 150 ^{14}C years BP. The second glacial advance was therefore sometime prior to 11000 BP and stagnant ice was decaying in the area over a time span of at least 2000 years (Emerson 1977).

Hastings Lake is shallow and of moderate size. Morphometric data are listed in table I. The smaller northeast basin comprises

Figure 1.

Morphometric map of Hastings Lake.



Hastings Cr.
NH-1
Coleman L.
CH-2
CH-1
Cooking Lake
Sisib L.
Hastings Lake
0
1km
N

Elevation	735m
Area (excluding islands)	$8.44 km^2$
Volume	$21.9 \times 10^6 m^3$
Length	6156m
Maximum width	2436m
Maximum depth	8.0m
Mean depth	2.5m
Shoreline length	35.52km
Shoreline development	3.40

Table I. Morphometric features of Hasting Lake (53° 30' N, 113° 00' W) (from Hickman and Jenkerson 1978).

some 19% of the surface area and 8% of the volume.

Some 50% of the watershed has been cleared for agriculture, largely pasture. Forest cover around the lake margin remains fairly intact. Populus tremuloides and P. balsamifera form the major components, with Picea glauca forming scattered small stands (Hickman and Jenkerson 1978). The lake lies within the Boreal Parkland Transition zone (Moss 1955).

Hastings is for the most part a closed system, with overflows occurring very irregularly. Physical conditions and phytoplankton production have been investigated by Hickman and Jenkerson (1978). During the ice-free period the lake remained isothermal, but during the winter inverse stratification occurred. Circulation was minimal at this time. Temperatures ranged from 19°C in early August to 0.2°C under winter ice. During the summer oxygen levels remained generally high, often supersaturated. In late summer and autumn the oxygen demand of the lower water column increased and there were periods when 30 to 50% saturation were observed. With the stabilization of the water column in winter, oxygen levels declined to less than 5% in the lower 3m.

Phytoplankton standing crop averaged 29.2mg m^{-3} and 73.1mg m^{-2} chlorophyll a respectively. No real pattern was evident in distribution by depth. In contrast phytoplankton primary production was strongly depth - dependent during the summer, although less so in the winter. Mean values were 78.71mg C hr^{-1} m^{-3} and 196.77mg C hr^{-1} m^{-2} on an annual basis. In early August rates in excess of 500mg C hr^{-1} m^{-3} were observed.

Cyanophycean algae, particularly Microcystis aeruginosa Kuetz.; emend. Elenkin, Oscillatoria sp. and Anabaena circinalis Rabenhorst, were dominant during summer, autumn and early winter. They were superceded by flagellated algae such as Chlamydomonas globosa Snow, Chryptomonas ovata Ehrenberg and Rhodomonas minuta Skuja under ice cover.

Phytoplankton contributes 92% of the algal production and 95% of the standing crop on an areal basis. The proportions for the epiphyton are 7.9% and 4% respectively, while for the epipelon they are 0.1% and 1% (C.G. Jenkerson and M. Hickman, unpublished data).

Lac Ste. Anne (fig. 2) is in the Sturgeon River basin, approximately 60km WNW of Edmonton. This area too was covered by the continental ice sheet during the late Wisconsin and at least once previously. It is thus underlain by glacial till derived from sources in the Precambrian shield to the northeast, rather than from the Cordillera (Collins and Swan 1955).

Deglaciation throughout Alberta was a relatively rapid phenomenon and, except where stagnant ice blocks such as in the Cooking Lakes area were left behind, periglacial processes had only a minor effect on the landscape (St. Onge 1972b). Deglaciation at Lac Ste. Anne occurred between 13500 and 10700 BP (St. Onge 1972b). The basins of Lac Ste. Anne were incorporated into glacial Lake Leduc, one of the

Figure 2.

Morphometric map of Lac Ste. Anne.


Sturgeon River
LSA
N
0
1km
Lac Ste Anne

complex series of large proglacial lakes which formed along the retreating ice margin (St. Onge 1972b). This permitted reworking of much of the till in the basin. Along the south and east shores of Lac Ste. Anne the surficial sediments have been strongly sorted and are predominantly interglacial sand. The southwestern shoreline, less affected by proglacial lacustrine processes, is a modified brown till with some indications of beach processes. To the north of the lake is a large area of ground moraine and massive brown till, unmodified by lacustrine events (Collins and Swan 1955).

The basin lies within the Boreal - Cordilleran Transition vegetation zone of Moss (1955), or the Aspen to Spruce Ecotone of North (1976), but it is very close to the boundary of prairie parkland. The modern arboreal component is totally dominated by Populus species, although Picea becomes important only a short distance to the northwest. Presently less than 50% of the basin is under cultivation.

The Sturgeon River flows from Lake Isle, to the west, through Lac Ste. Anne to the North Saskatchewan River. The flow is rarely if ever interrupted, but may become quite low during the summer and winter. Morphometric data on Lac Ste. Anne are listed in table II. The lake is

Elevation	730m
Area	$56.49 km^2$
Volume	$273.25 \times 10^6 m^3$
Maximum depth	9.14m
Mean depth	4.84m
Shoreline length	54.71km
Shoreline development	2.05
Water residence time	6.4 years

Table II. Morphometric features of Lac Ste. Anne (53° 42' N, 114° 21' W) (from Reynoldson 1977).

relatively large for this area, shallow, exposed and productive. It consists of two large basins joined by an extremely narrow and shallow channel. The two basins are probably functionally separate. While the lake has seen considerable fisheries research, published information on the general limnology is not available. Preliminary investigations by Alberta Environment as part of the Sturgeon River Basin Study have provided some information (Reynoldson 1977, D.J. Beliveau, personal communication).

Mean summer (June to October) standing crop of phytoplankton is in the order of 24mg chlorophyll $\underline{a}$ m^{-3}. This is somewhat less than the mean annual value for Hastings Lake, indicating that Lac Ste. Anne is less productive. There is evidence for local oxygen depletion, to 16% saturation, in late summer. This becomes more pronounced in winter, but never reaches 0% (C. Thoreson, personal communication). Lac Ste. Anne is non-stratifying in summer, but presumably is inversely stratified in winter.

In terms of climate, Lac Ste. Anne experiences slightly cooler summers and slightly warmer winters than Hastings. Mean annual precipitation at Hastings is approximately 45cm, as opposed to 50cm at Lac Ste. Anne (North 1976).

Published paleolimnological research in Alberta is minimal. St. Onge (1972b) has reconstructed proglacial lake sequences; Harris and Pip (1973) have studied molluscan remains in proglacial lake sediments and alluvium; Lichti-Federovich (1970 and 1972) has carried out pollen analytical studies in east central Alberta. This study forms part of a larger programme of paleolimnological research being carried out in the botany and anthropology departments at the University of Alberta

for which preliminary reports have been issued (Forbes and Hickman 1978, Klarer and Hickman 1978, Hickman et al. 1978). This programme is the first to focus on the history of processes within Alberta lakes, particularly with respect to biological events.

METHODS

1. Coring

In February 1976 two sediment cores were obtained from Hastings Lake. CH-1 was taken in 7.3m of water from near the deepest point of the main basin. NH-1 was taken in 3.0m of water in the middle of the northeast basin. A third core, CH-2, was obtained 50 to 100m from the site of CH-1 in 7.0m of water during February 1977. In March 1977 two cores, LSA-1 and LSA-2, were retrieved from near the centre of the main basin of Lac Ste. Anne. They were from points approximately 10m apart.

A modified Livingston piston corer (Wright et al. 1965) with an internal diameter of 5.08cm and a length of 1.0m was used in all cases. Lake ice provided a stable working platform. Core sections were extruded in the field to permit cursory examination, detection of any obvious contamination problems, and measurement of sample recovery. They were then immediately wrapped in light plastic, with an outer cover of heavy brown paper to reduce exposure to light and air to a minimum. The cores were taken to the laboratory and stored in the dark at 4°C until sampled.

A light surface sampler was used to obtain a surficial sample from the main basin of Hastings Lake in November 1977. Samples from the uppermost sediments of Lac Ste. Anne were obtained for pollen analysis by a freezing method. The core barrel was filled with dry ice, sealed and lowered so that it straddled the mud-water interface. After 15 minutes the barrel was raised together with adhering sediment, wrapped and taken to the laboratory where it was stored frozen until sampled.

2. Analysis

At the time of sampling each core section was remeasured and described with respect to composition, texture, structure, inclusions and colour. The Revised Standard Soil Color Charts (Oyama and Takehara 1970) were used as a basis for colour comparison. After carefully scraping away the outer portion of the core sections, they were sampled at intervals of 5cm. In some cases intermediate samples at 2.5cm were taken.

Samples for pollen analysis (1.0cc wet sediment), organic matter analyses (1.0cc wet sediment) and radiocarbon dating (5cm slugs) were taken from CH-1, NH-1 and LSA-1. Pollen analysis of CH-1 was carried out by D. Emerson (unpublished data).

Following Wetzel (1970) water content was measured as weight loss after overnight drying at 105°C, organic matter after ignition at 550°C for one hour, and carbonates after further ignition at 950°C for three hours. Water content is expressed as a percentage of wet weight; organic matter and carbonates as a percentage of dry weight.

Samples for radiocarbon dating were air-dried or freeze-dried, wrapped in aluminum foil and sent to Dicarb Radioisotope Laboratories, Chagrin Falls, Ohio, for analysis.

From CH-2, NH-1 and LSA-2, 2.0cc samples of wet sediment were taken for pigment studies. The remainder of these cores was divided into 5cm or 2.5cm slugs, freeze-dried and ground to a fine consistency. These samples were used for the rest of the nutrient and metal analyses.

Pigments were extracted in approximately 15ml 90% acetone by homogenization for about 15 seconds with a Polytron PCU-2-110

(Brinkman Instruments), followed by centrifugation. Samples were then made up to 20.0ml and pigment concentrations determined by spectrophotometry. Complete extraction by this technique was confirmed by second extractions of a number of samples, which yielded no detectable pigments. Optical density at 665nm was used to measure total a pigments (TaP) and at 480nm to measure total carotenoids (TC). In both cases the optical density at 750nm was subtracted to correct for turbidity. Results are expressed, both on a cc^{-1} wet sediment basis and a g^{-1} organic matter basis, in arbitrary units. One unit equals an optical density of 0.100 for a sample extracted in 10ml solvent, through a path length of 1.0cm. This is quantitatively equivalent to the SCDP unit of Vallentyne (1955).

For the remaining chemical analyses, apart from nitrogen, 100mg of dried sample was placed in the teflon cup of an acid digestion bomb and digested in 1.0ml aqua regia, plus 5.0ml 48% hydrofluoric acid for two hours at 135°C. The digestion was carried out in an oven within a fume hood. After cooling, the digest was transferred to a 100ml volumetric flask containing 2.9g boric acid and 20ml deionized water. This was shaken until all the boric acid had dissolved, made up to 100ml with deionized water and stored in acid-washed Nalgene bottles (Loring and Rantala 1977).

Calcium, cobalt, copper, iron, magnesium, manganese, nickel, lead and zinc were determined by atomic absorption spectrophotometry. Sodium and potassium were analysed by flame photometry. Analyses of cobalt, copper, nickel and lead were not considered further as some or all determinations were near or below the limits of sensitivity.

Sulphate was analysed by the turbidometric method (APHA et al.

1976). Glycerol was found to cause interference in the strongly acidic digest. It was eliminated from the procedure and satisfactory sensitivity was obtained.

Total phosphorus was determined by the stannous chloride method, with colour read spectrophotometrically at 690nm (APHA et al. 1976). Glycerol was again found to cause interference, so the stannous chloride reagent without glycerol given by Mackereth (1963) was used.

For determinations of nitrogen, 100mg dry sediment was extracted by micro-Kjeldahl digestion and analysed by a Technicon autoanalyser (APHA et al. 1976). Results are expressed as total Kjeldahl nitrogen (TKN).

Units for all nutrient and metal analyses are $\mu g\ g^{-1}$ or $mg\ g^{-1}$ dry weight as appropriate.

Pollen extraction from the Lac Ste. Anne sediments was by a modification of Faegri and Iversen (1975) as follows: sodium hydroxide treatment, hydrochloric acid,hydrofluoric acid, glacial acetic acid, acetolysis, glacial acetic acid, transfer to acetone and mounting in glycerol, with appropriate intermediate washings and screening. Results are expressed as percentages of total pollen, including both terrestrial and aquatic. Pollen sums comprised a minimum of 300 grains, including aquatics but excluding indeterminants and spores.

RESULTS

1. Hastings Lake

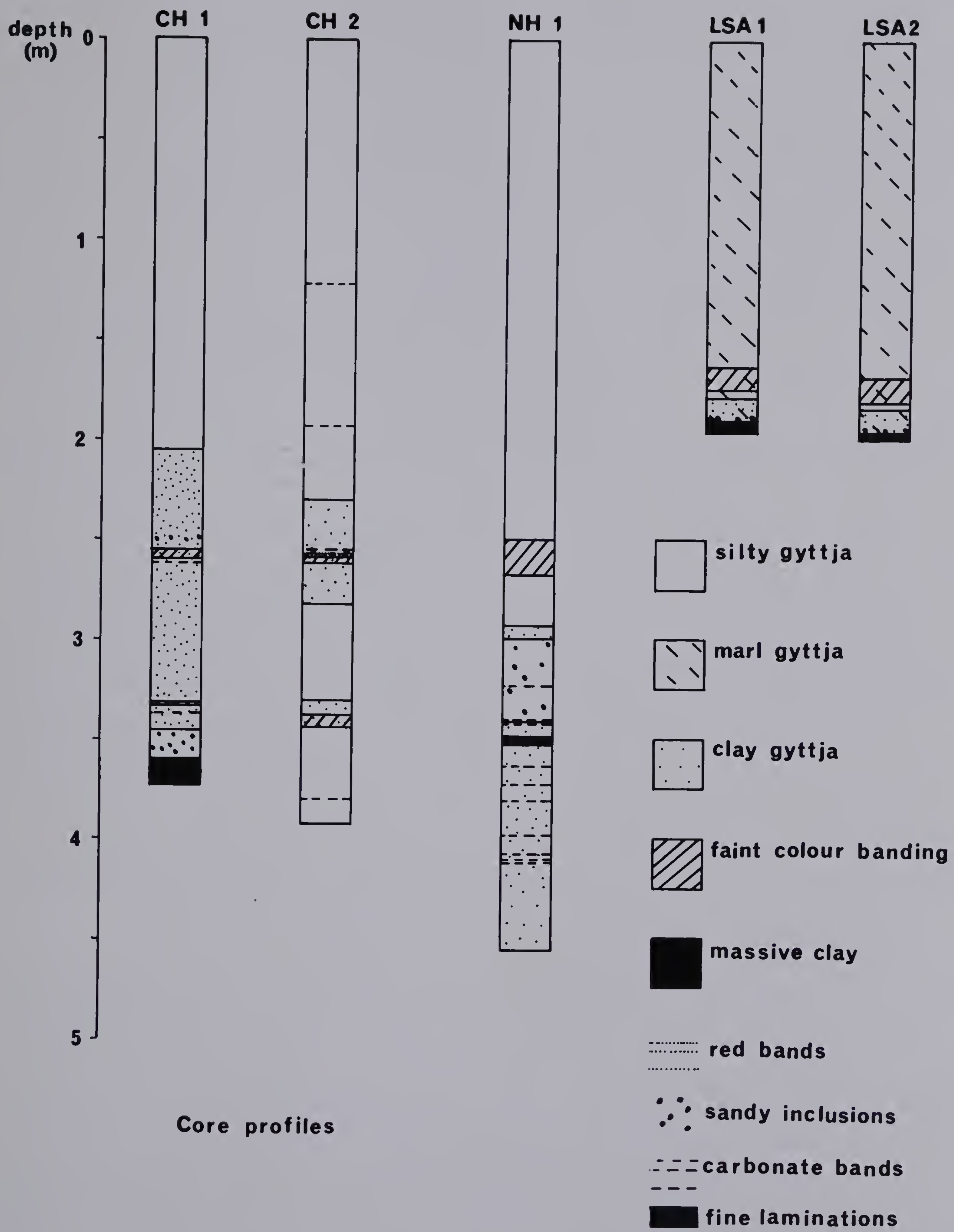
a. Physical structure

The cores CH-1 and CH-2 differed considerably in stratigraphic detail (fig. 3a,b), despite originating at more or less the same depth of water and being taken within 100m of each other. Precise correlation has proved impossible. 373.2cm of core were recovered from CH-1. This penetrated some 14cm into a heavy grey basal clay of extremely low organic content. In contrast CH-2 was 393.2cm in length and maintained a higher organic content with comparatively less clay right to the base.

The top 205cm of CH-1 comprised a slightly silty organic gyttja with no distinct changes in texture or structure. Some very faint mottling and banding was noted, but in general this section was reasonably homogeneous. Colour ranged between 2.5Y 3/2 (brownish black) and 5Y 3/2 (olive black). From 205 to 248cm there was an increasing clay content, but little change in structure. Between 248 and 251cm fine sandy pockets were also noted. The enhanced silt and clay content of the gyttja continued. From 255.7 to 259.7cm very faint but even bedding was observed, with a total of eleven alternating light and dark bands (5Y 4/2 (greyish olive); 5Y 3/2 (olive black)). Below this there was a very gradual increase in clay content with little other change of note. There were two very thin carbonate bands at 263.3 and 338.0cm; some faint bedding as above between 332.2 and 334.8cm; and some minor variations in the degree of mottling. From 346 to 359cm there was a reversal, with silt becoming more prominent than clay. Within this area there was also a considerable quantity of fine sand, concentrated especially between 357 and 358cm. This composition changed fairly

Figure 3.

Stratigraphy of cores CH-1, CH-2, NH-1, LSA-1 and LSA-2.



Core profiles

abruptly between 359 and 360cm, below which the core comprised the massive grey clay described above.

The upper portion of CH-2 was similarly an organic gyttja with few significant features. Again the colour ranged between 2.5Y 3/2 and 5Y 3/2. There were two very thin carbonate bands at 124.1 and 193.5 cm, but otherwise only minor variations in mottling down to 231cm, where an increasing clay content became apparent. A region with sandy inclusions from 254.7 to 256.5cm corresponded to the similar band in CH-1 around 250cm. Macrophyte roots were also seen here. There were two very thin red bands, 5R 3/3 (dark reddish brown), at 257.9 and 258.1cm. Faint bedding occurred between 259.7 and 263.2cm, possibly corresponding to that between 255 and 259cm in CH-1. Below this there were few changes of note for some distance. From 283 to 332cm there was a relative increase in silt content, but below this clay again became the dominant mineral constituent. There was a region of faint banding between 337.1 and 344.8cm. From this point the clay - silt balance again reversed, continuing with silt dominant to the base of the core at 393.2cm. Apart from a carbonate band at 381cm no other distinctive features were apparent. No sand was observed near the base of the core.

Compared to the main basin the sediments of the northeast basin were visibly much more organic in character. From the top of NH-1 to 293.8cm silt was the major inorganic constituent, but the sediment was overwhelmingly gyttja. The colour was fairly consistently 2.5Y 3/2 (brownish black), with only minor variations. There were fairly distinct colour bands between 250.7 and 268.3cm (2.5Y 3/2, 5Y 3/1.5 (olive black), 2.5Y 3/2, 10YR 2/3 (brownish black), 2.5Y 3/2.5 (dark olive brown)). From 294 to 300cm the clay content was enhanced.

Below this silt was again more prominent than clay. From 341.4cm to the base at 456.4cm clay was the dominant inorganic component. From 300 to 340cm there were occassional small inclusions of sand. Very thin, single carbonate bands were observed at 323.6, 340.7, 341.8, 363.5, 373.2, 381.0, 394.1, 408.8, 410.7 and 411.6cm. Between 374.2 and 377.9cm very fine bands of carbonate alternating with layers of gyttja gave the impression of annual laminations. There were approximately 14 beds cm^{-1}. Apart from this there were no significant structural changes in the core. No sandy inclusions or massive clay were observed at the base of the core.

b. Chronology

Four radiocarbon dates were obtained for CH-1, of which one was discarded as anomolous. In addition basal dates were obtained for CH-2 and NH-1. These are listed in table III. No corrections have been applied to any of the dates. All dates discussed below are expressed in ^{14}C years BP unless otherwise noted.

	DEPTH	RADIOCARBON DATE
CH-1	97.5cm	2710±290 ^{14}C years BP
	295.0cm	4450±215 ^{14}C years BP
	345.0cm	4580±190 ^{14}C years BP
CH-2	385.5cm	4780± 80 ^{14}C years BP
NH-1	433.5cm	3890±100 ^{14}C years BP

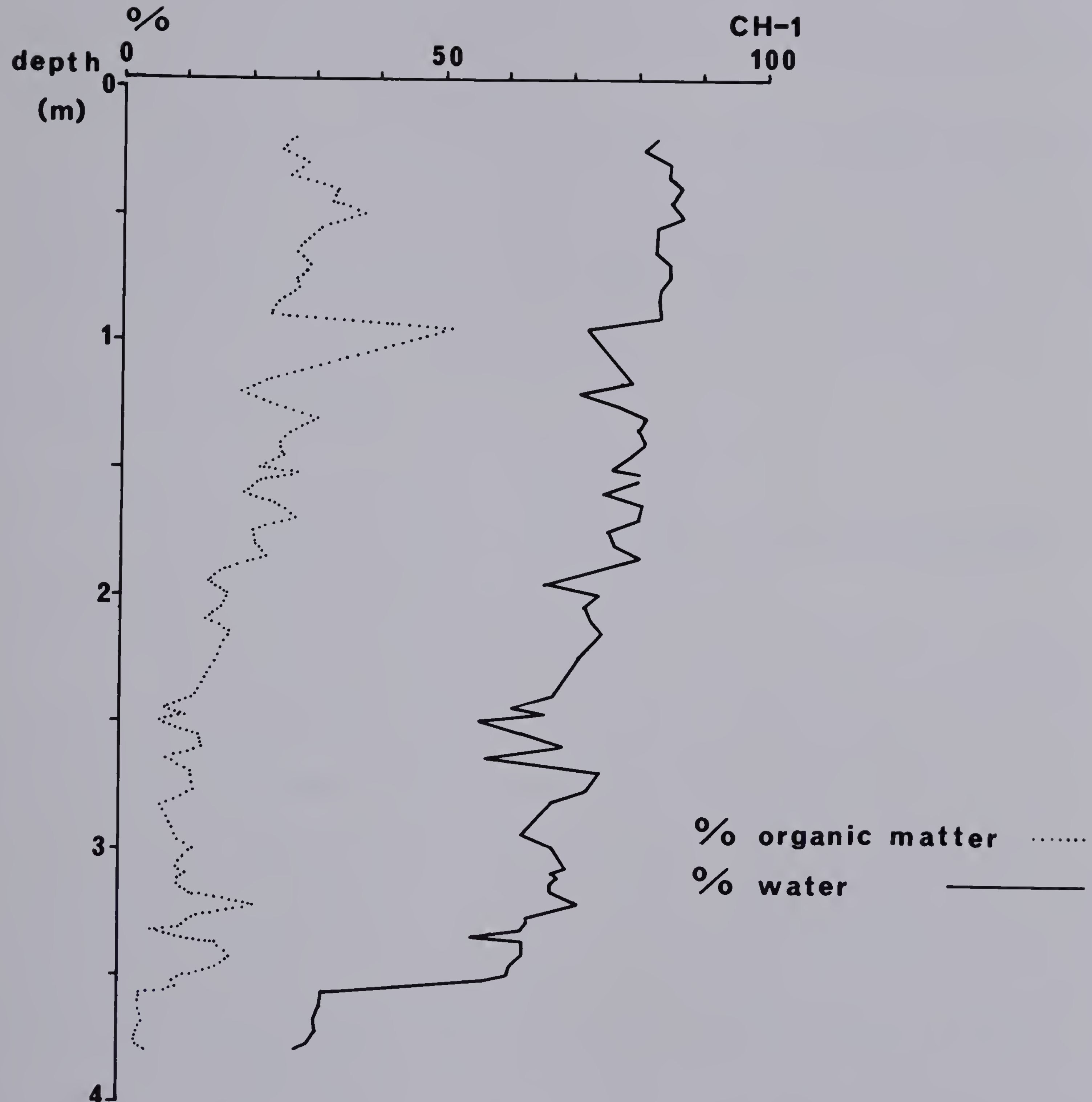
Table III. Radiocarbon ages of sediment samples from Hastings Lake

c. Water content

Interstitial water content is largely a function of grain size distribution and compression. In CH-1 water content (fig. 4)

Figure 4.

CH-1: % organic matter (as % of dry weight) and % water content (as % of wet weight).



%
CH-1
depth
(m)
0
50
100
0
1
2
3
4
% organic matter
% water

generally declined very slowly from the surface to 350cm where there was an abrupt drop as the heavy grey clay became dominant. Per cent water content near the surface was in the order of 85%; at 350cm it had dropped to 60%; below this it was somewhat less than 30%. Above the clay there were three subtle bulges, with peaks at 50, 165 and 270cm. There were intermediate lows at 100 and 250cm.

Water content in NH-1 (fig. 5) was slightly higher throughout the core, with values from 15 to 100cm ranging from 85 to 92.5%; those from 100 to 275cm running generally between 80 and 85%; then a more rapid decrease to values around 45% at the base. There were two distinct troughs at 300 and 350cm.

d. Organic matter, nitrogen and phosphorus

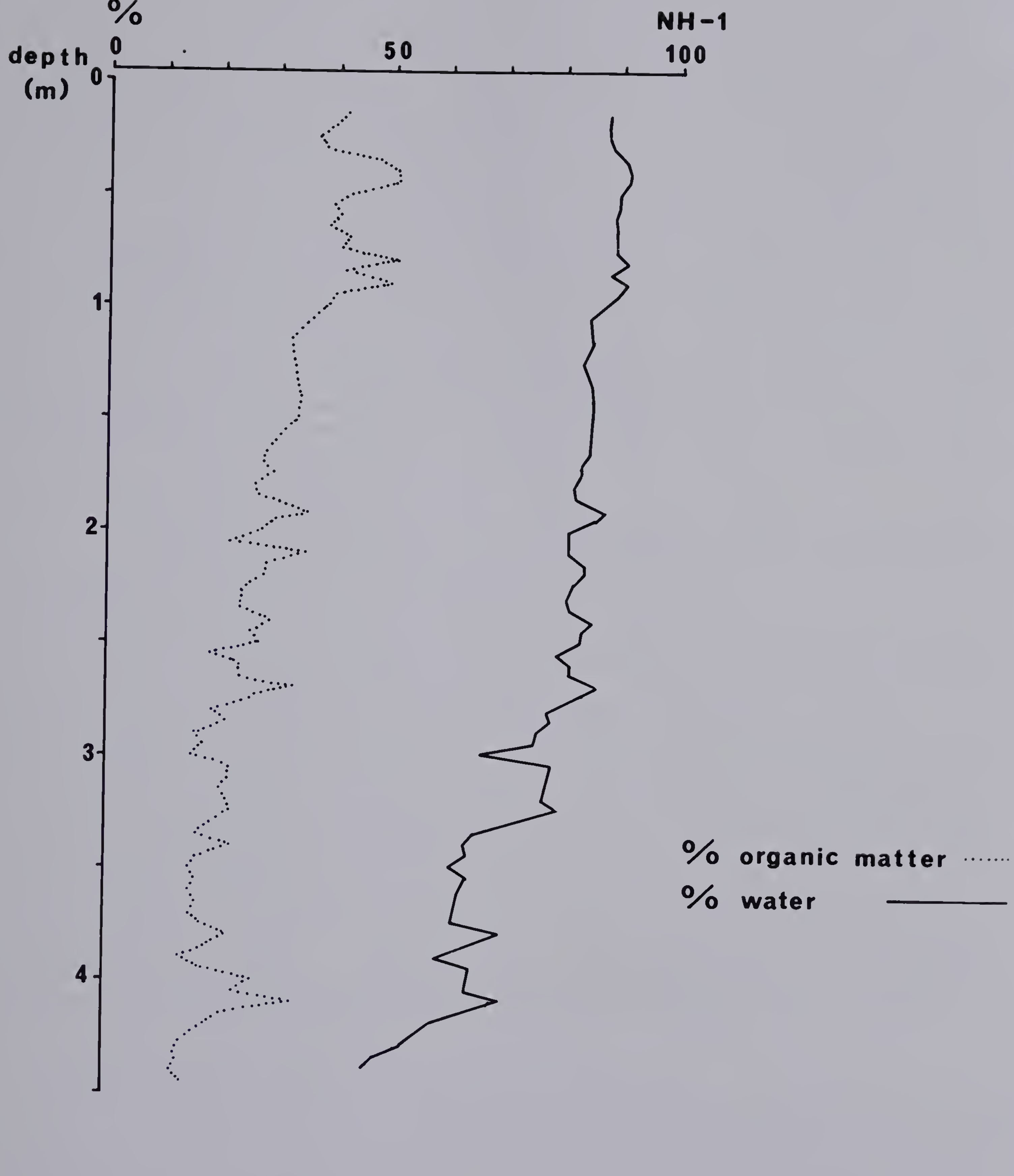
The organic content of the sediments showed an increasing trend from the base towards the surface in Hastings.

In the central basin (fig. 4) the basal samples had very low amounts of organic matter, between 2 and 4%. From 355cm up there was a fairly rapid increase to a peak at 342.5cm, then a tailing off before a steadily increasing trend established itself. This continued up the core to a peak at 50cm of 38% organic matter, before dropping moderately towards the surface. A slight area of decline around 100cm is offset by the anomolous sample at 95cm, which had over 50% organic matter.

The pattern of organic matter contents in the core from the northeast basin (fig. 5) was very similar, although the total quantities here were considerably greater than in the central basin. Basal levels were in the order of 12% and again increased fairly rapidly to a small peak at 410cm depth, with 33% organic matter. The levels fell off to around 15% before gradually increasing up the core to peak at around

Figure 5.

NH-1: % organic matter (as % of dry weight) and % water content (as % of wet weight).



%
NH-1
depth
(m)
0
50
100
0
1
2
3
4
% organic matter
% water

45cm with over 50% organic matter. Above this the percentages fell off a little.

Both basins had increasing accumulations of nitrogen in their sediments (fig. 6a, 7a). From the base to 200cm in CH-2 TKN values ranged between 5 and 10mg g^{-1}, with peaks at 370, 320 and 240cm. Above 200cm there was considerably more TKN; quantities ranged between 15 and 24mg g^{-1}. There were two peaks here: at 160 and 75cm. TKN values in NH-1 increased more evenly up the core, from 6 to 10mg g^{-1} near the base to between 26 and 30mg g^{-1} in the upper 100cm. There were minor peaks at 410, 265 and 190cm. A broad area of enhanced values between 85 and 35cm eased somewhat near the surface. Overall TKN levels in the northeast basin were higher than in the main basin.

The tendency observed in other elements to increase with time was much less evident in the profile of phosphorus. In CH-2 (fig. 6b) most values below 200cm were between 3 and 5µg g^{-1}. However there were peaks of 6.8 and 6.4µg g^{-1} at 375 and 250cm respectively. PO_4-P values above 200cm ranged from 5 to 9.5µg g^{-1}, with peaks at 110 and 85cm and a slight decline evident nearer the surface. In NH-1 (fig. 7b) there were few points with PO_4-4 values of less than 5µg g^{-1}, apart from a depression to 3.7µg g^{-1} around 330cm. The maximum value was 9.4µg g^{-1} at 60cm and there were other less prominent peaks at 415 and 220cm.

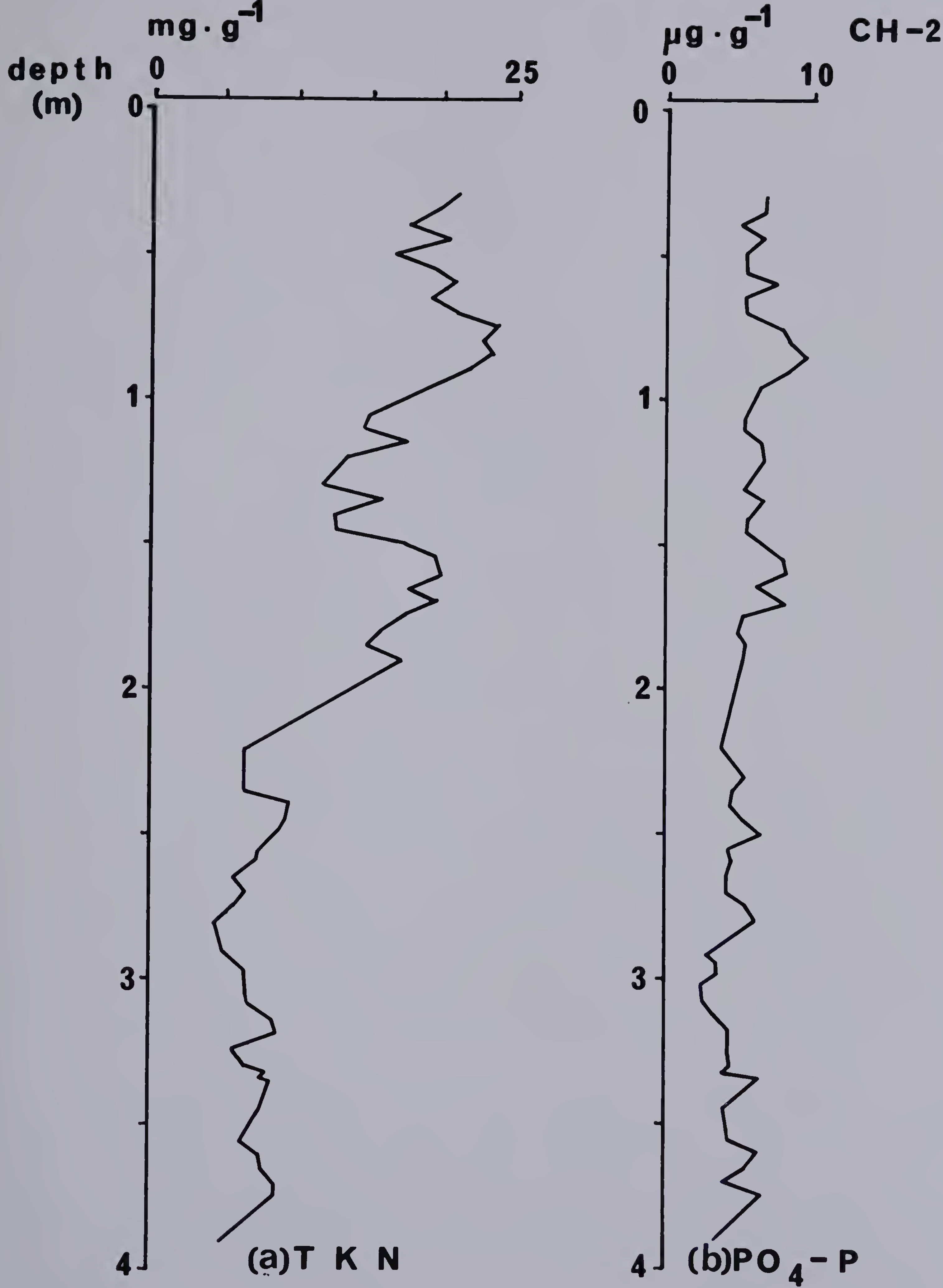
e. Total a pigments and total carotenoids

TaP in the centre of the lake (fig. 8) showed the distinctive pattern of low levels in the basal half of the core and higher levels above. Close to the base the values were irregular, but had a definite minimum around 285cm. From here there was a gradual but irregular increase to a broad bulge between 165 and 85cm. In this area TaP values

Figure 6.

a. CH-2: total Kjeldahl nitrogen (mg g^{-1} dry weight).

b. CH-2: total phosphorus as PO_4 - P (μg g^{-1} dry weight).

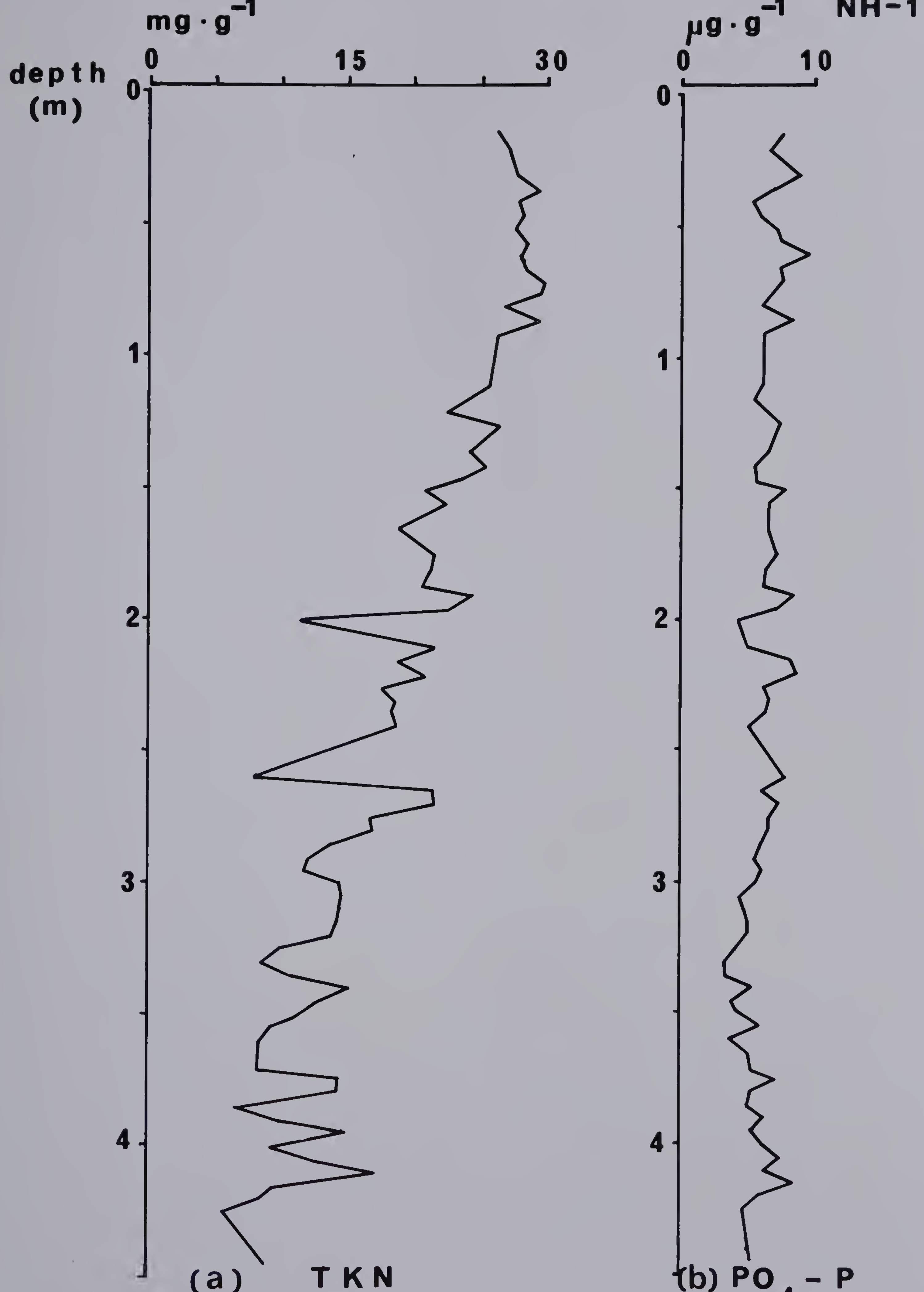


depth
(m)
mg · g⁻¹
0
25
μg · g⁻¹
0
10
CH-2
0
1
2
3
4
(a)T K N
(b)PO4-P

Figure 7.

a. NH-1: total Kjeldahl nitrogen (mg g^{-1} dry weight).

b. NH-1: total phosphorus as PO_4 - P (μg g^{-1} dry weight).



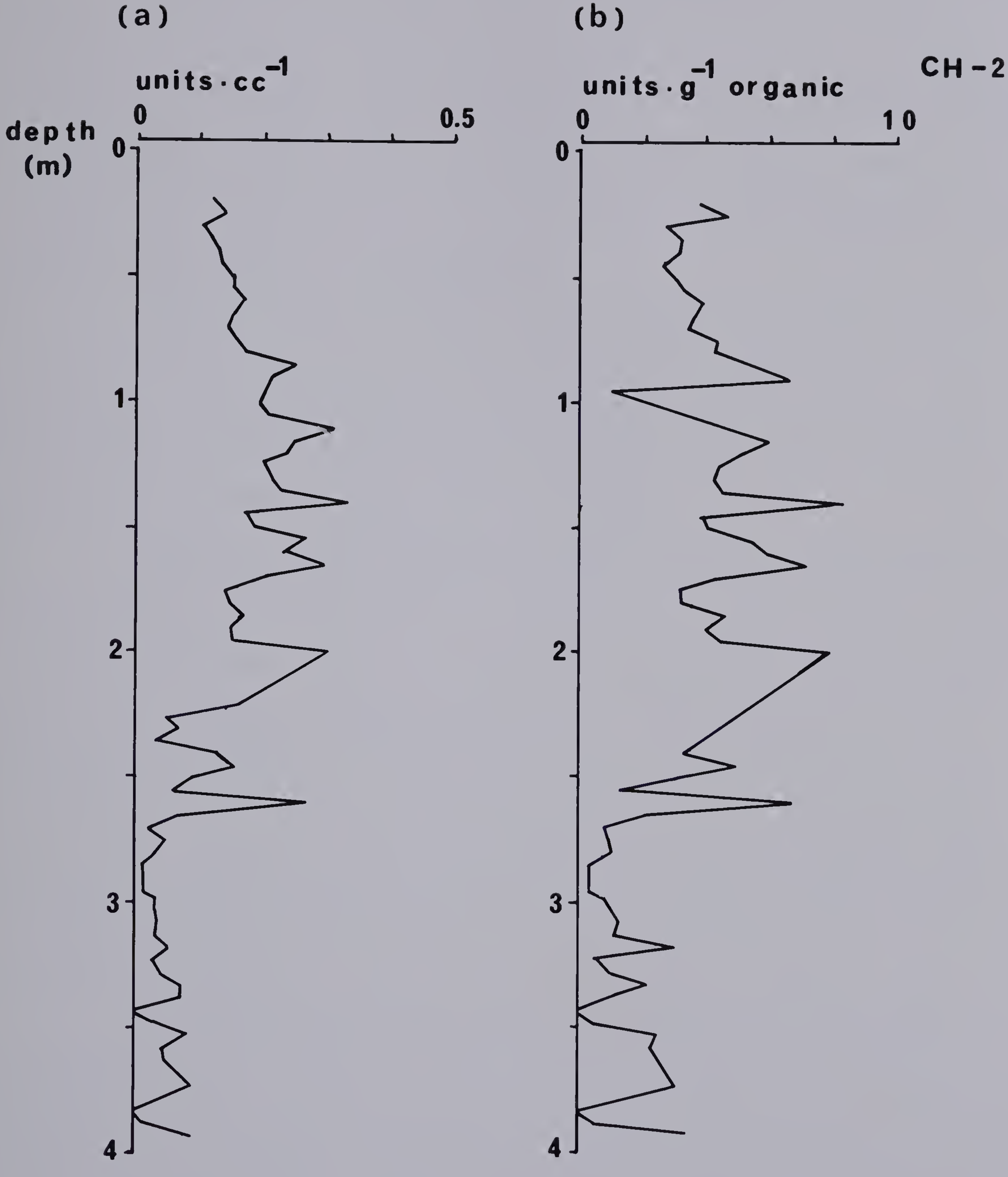
(a) TKN

(b) PO_4 - P

Figure 8.

a. CH-2: total <u>a</u> pigments (SCDP units cc^{-1} wet sediment).

b. CH-2: total <u>a</u> pigments (SCDP units g^{-1} organic matter).



T a P

ranged from 0.2 to 0.3 SCDP units. Above this there was a decline towards the top of the core where analysis indicated 0.1 SCDP unit.

The northeast basin had a rather different pattern (fig. 10). Although TaP values at the base were low, there were no other major anomolies in the core. Values generally fluctuated irregularly about 0.2 SCDP unit. In the upper 2m of the core there appeared to be a slight decline. Minor peaks at 125, 90, 45 and 15cm gave the impression of a fairly regular cycle of low amplitude.

When expressed on a g^{-1} organic matter basis, TaP (fig. 8b, 10b) showed little deviation from the patterns discussed above. With the general increase in organic matter up the cores, TaP g^{-1} organic matter was somewhat enhanced toward the base of the cores.

Despite greater sample to sample variability, the pattern of total carotenoids in CH-2 (fig. 9) roughly corresponded to that of TaP, with two exceptions. There was a distinct peak about 250cm and there was a very irregular pattern near the base. Some samples here had extremely high TC levels. For example the sample at 383cm measured 10.27 units. Only one other sample exceeded 6.0 units (388cm), while elsewhere TC were generally below 2.0 units. In the troughs from 328 to 280cm and above 75cm TC levels were less than 1.0 unit.

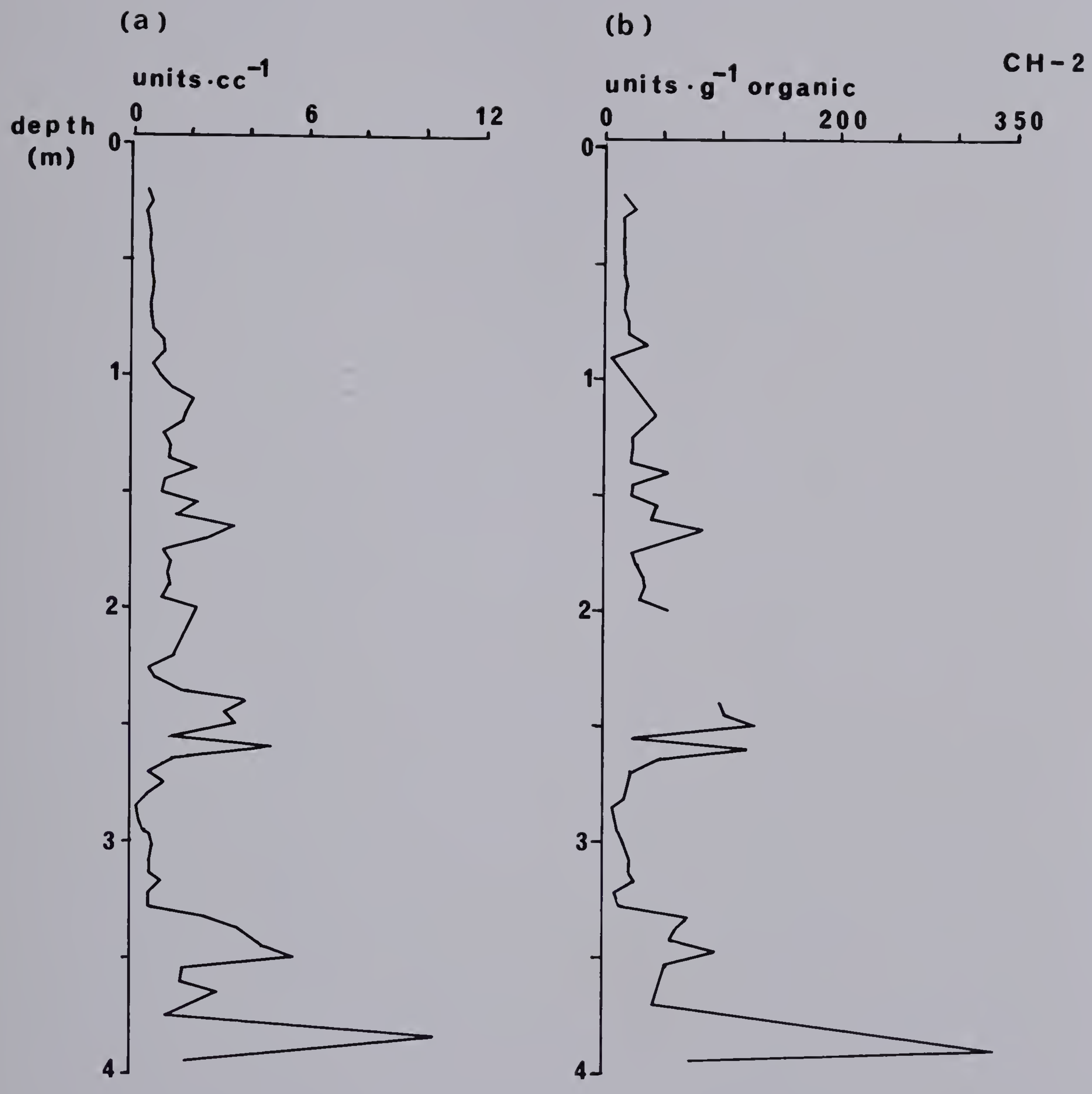
In the northeast basin (fig. 11) there was a very close correspondance of the distribution of carotenoids to that of the a pigments. Low levels at the base rose rapidly. Throughout most of the core values were quite irregular and without pattern, but there was a general reduction in the upper 1.5m. Here the same minor cyclic pattern appeared as in the a pigments.

Again conversion of results to a g^{-1} organic matter basis

Figure 9.

a. CH-2: total carotenoids (units cc^{-1} wet sediment).

b. CH-2: total carotenoids (units g^{-1} organic matter).

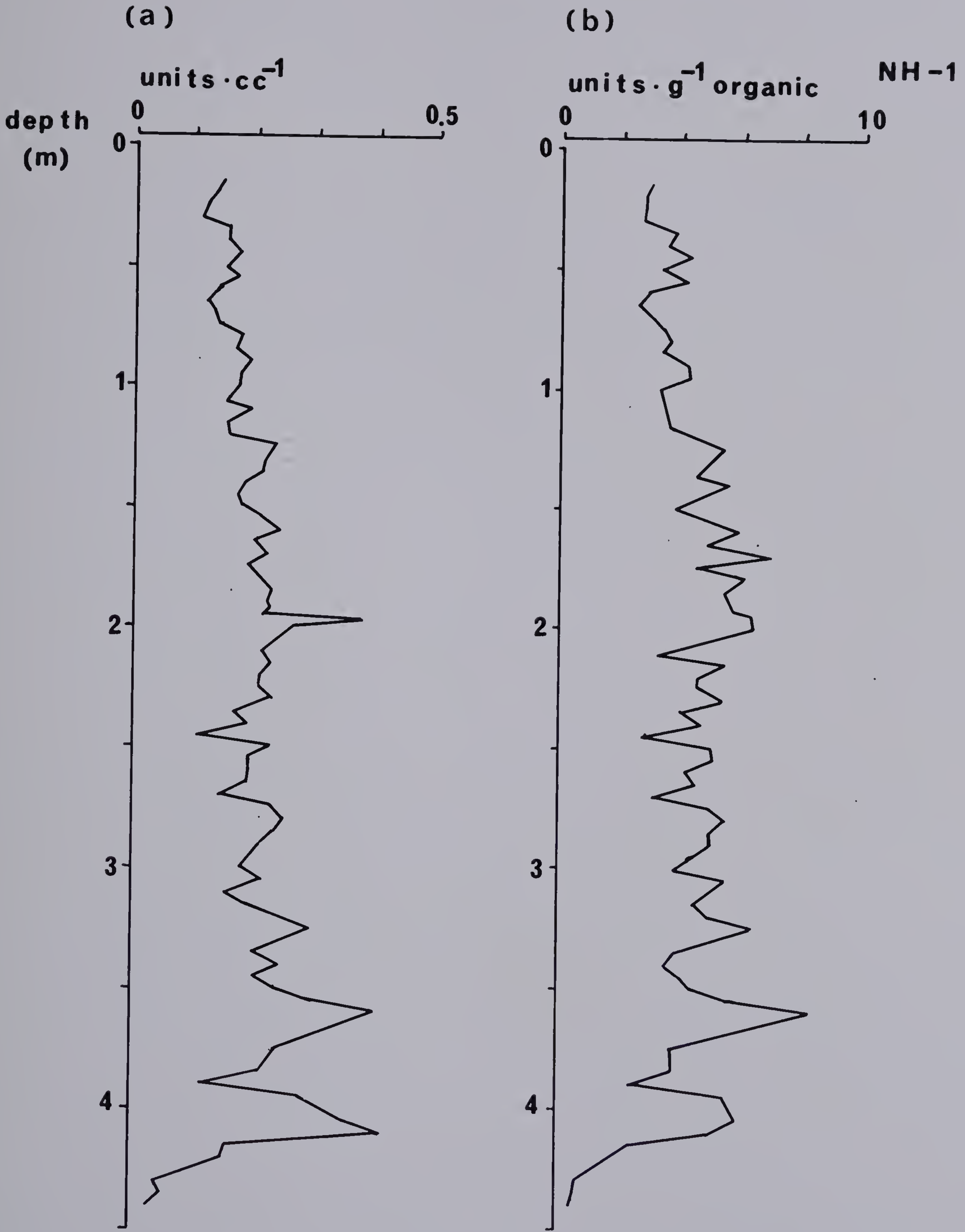


T C

Figure 10.

a. NH-1: total _a_ pigments (SCDP units cc^{-1} wet sediment).

b. NH-1: total _a_ pigments (SCDP units g^{-1} organic matter).

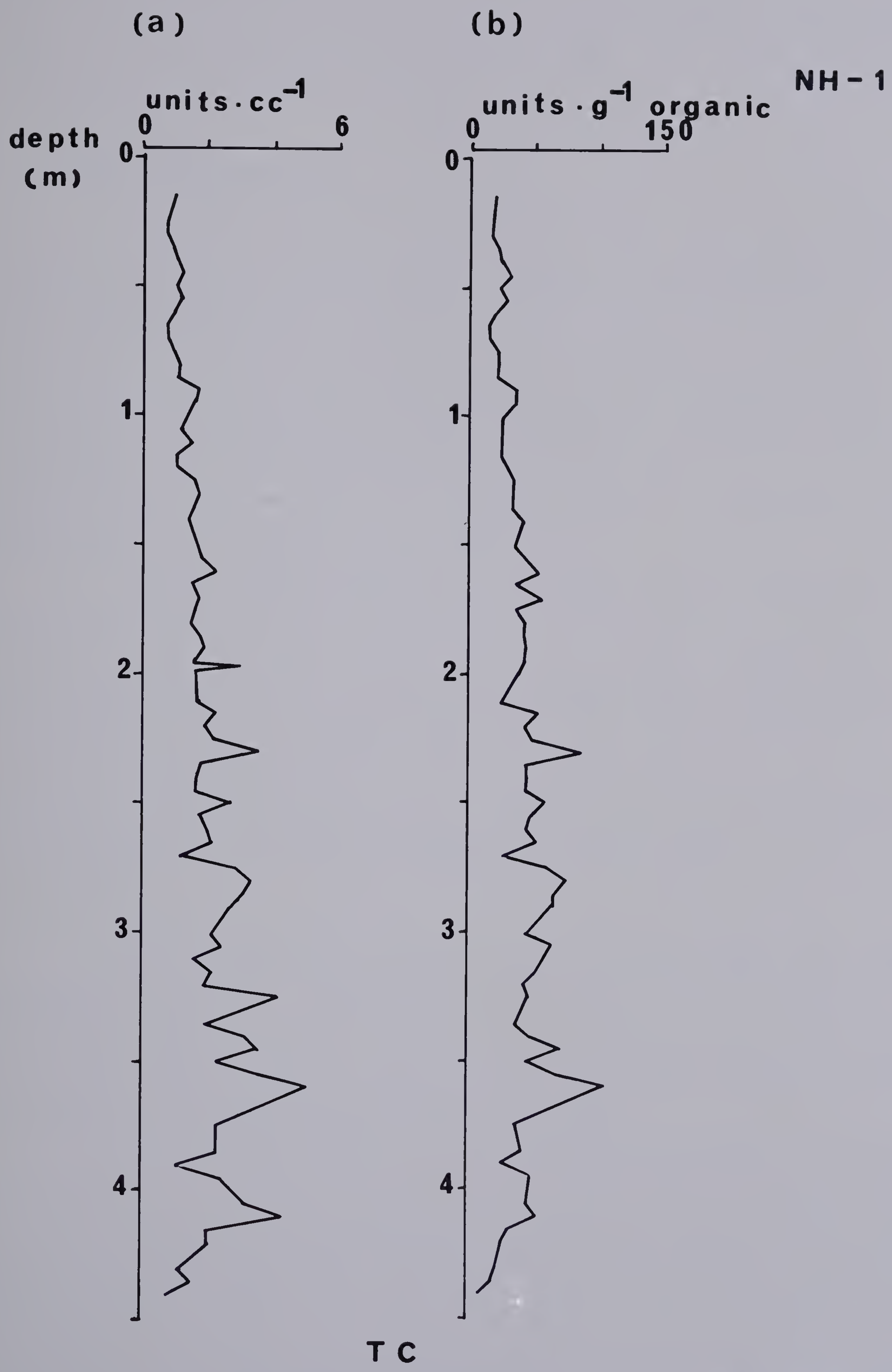


T <u>a</u> P

Figure 11.

a. NH-1: total carotenoids (units cc^{-1} wet sediment).

b. NH-1: total carotenoids (units g^{-1} organic matter).


(a)
(b)
NH - 1
units · cc⁻¹
0
6
depth
(m)
units · g⁻¹ organic
0
150
0
1
2
3
4
T C

(fig. 9b, 11b) did not change the patterns substantially. Values near the base of the cores were enhanced and, in the case of CH-2, the peaks at the base and around 250cm became extremely pronounced.

f. Calcium and carbonates

The distribution of calcium in CH-2 (fig. 12b) was remarkably similar to the pattern of a pigments. Values in the bottom half of the core were generally low, in the order of 10 to 40mg g^{-1} dry weight. There was a distinct trough in the area of 300cm. In the upper half of the core the calcium levels rose considerably. Most of the samples from 190 to 90cm were in the range of 60 to 85mg g^{-1}. Above this values again declined to between 40 and 60mg g^{-1}.

The pattern of carbonates in the lower portion of CH-1 (fig. 12a) was not dissimilar: low basal levels and a rather distinct peak about 350cm, falling to a definite minimum about 300cm. Above this the carbonates rose again, but the upper half of the core did not have as enhanced levels as those of calcium. Samples here were generally between 50 and 100mg g^{-1} dry weight of carbonates, with no regular pattern of distribution.

The distribution of calcium in the northeast basin (fig. 13b) did not show the close correspondence to a pigments that was found in the central basin. However in this core it did follow much more closely the pattern of carbonate distribution (fig. 13a).

Low levels of calcium at the base rose to a peak around 415cm and then dropped to lower but irregular amounts from 400 to 340cm. Above this calcium again increased. Between 325 and 100cm samples generally fell between 60 and 90mg g^{-1}, with no distinct pattern. From 80 to 30cm the calcium levels were extremely low, from 3 to 8mg g^{-1}, apart from the

Figure 12.

a. CH-1: carbonates (mg g^{-1} dry weight).

b. CH-2: calcium (mg g^{-1} dry weight).

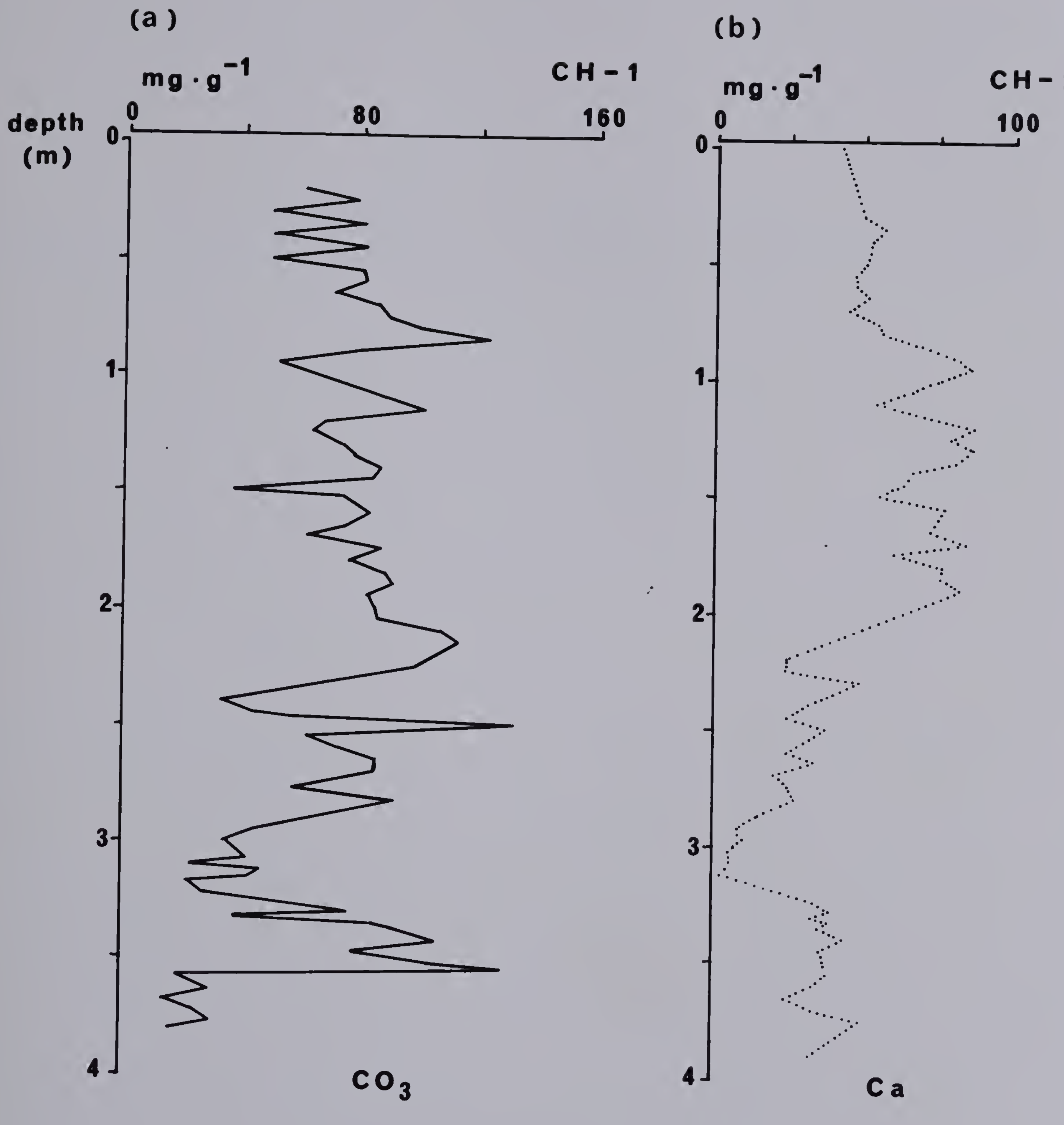
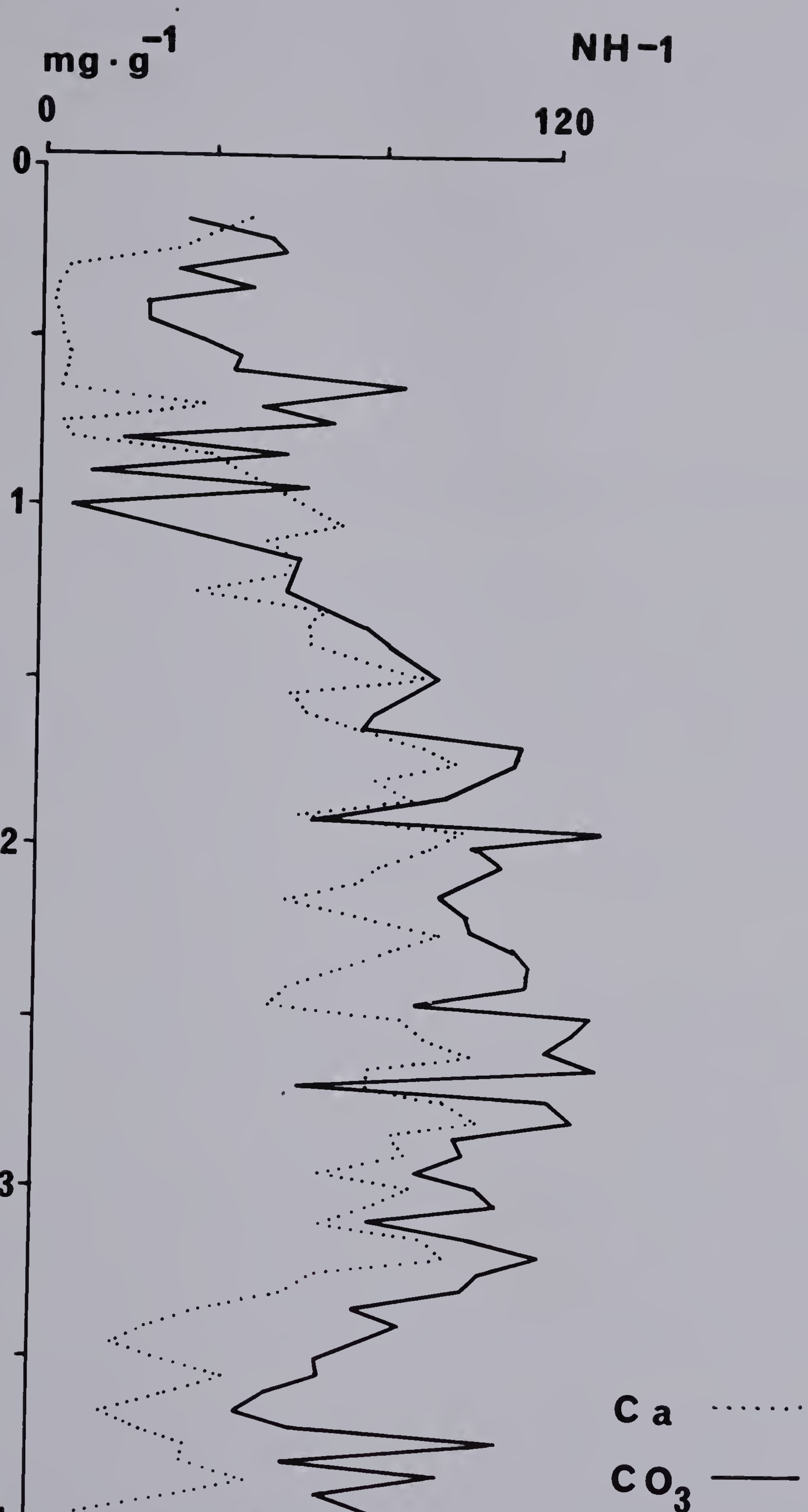

(a)
mg · g⁻¹
CH - 1
depth (m)
0
80
160
0
1
2
3
4
CO₃
(b)
mg · g⁻¹
CH - 2
0
100
0
1
2
3
4
Ca

Figure 13.

NH-1: carbonates (mg g^{-1} dry weight) and calcium (mg g^{-1} dry weight).


mg · g⁻¹
NH-1
0
120
0
1
2
3
4
Ca
CO3

sample at 70cm which had 38mg g^{-1}.

Carbonates in the northeast basin, as noted above, followed calcium quite closely. The peaks and troughs were less well-defined and from 80 to 30cm, where calcium dropped off significantly, there was no sign of depressed carbonate accumulations relative to adjacent samples.

g. Iron and manganese

The profiles of iron and manganese were quite coherent, with little internal noise.

Iron levels in the lower half of CH-2 (fig. 14a) were somewhat higher than in the upper half. Moving up from the base, there was a slight low about 350cm. From here to 220cm the profile formed a broad bulge, peaking around 275 to 300cm. In the upper 2m of the core iron levels, though lower, were fairly steady except for a broad shallow depression from 100 to 75cm.

In contrast to iron, manganese levels (fig. 14b) in the lower half of the core were generally less than in the upper half. The basal sample was quite low. Above this there was a slight rise, then a depression around 350cm. Manganese rose again to a peak around 325cm, then eased off to a trough around 240cm. There was a gradual rise in levels up to 130cm, a slight decline, then relatively constant values from 100cm upwards.

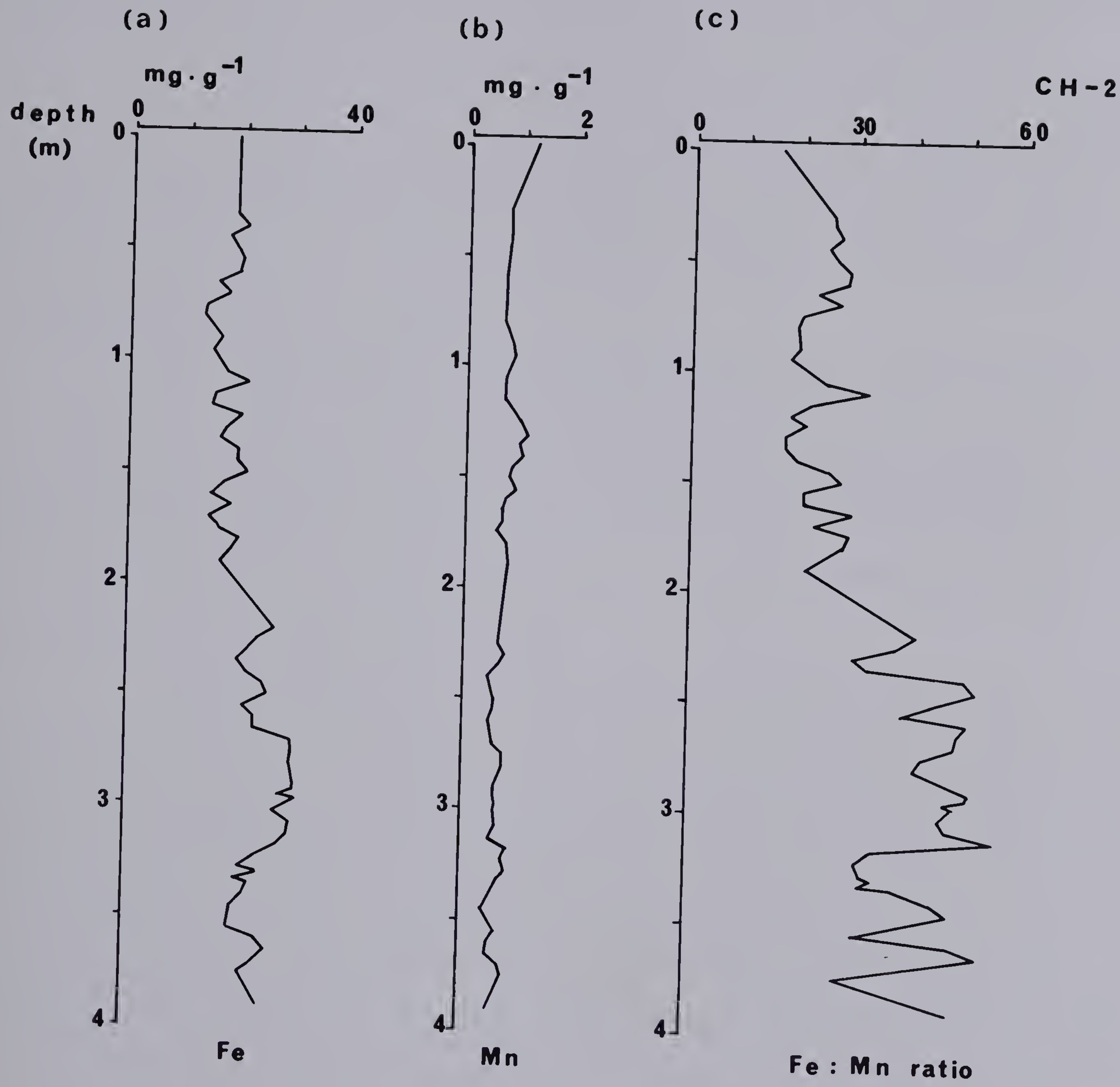
The relative decline of iron in the upper 2m of CH-2 and the slight enrichment of manganese had a rather profound effect on the iron: manganese ratio (fig. 14c). In the lower 2m the ratio was generally high, ranging from 350 to 450 for the most part. Above this only one sample exceeded 300; most fell between 150 and 250. As in other profiles

Figure 14.

a. CH-2: iron (mg g^{-1} dry weight).

b. CH-2: manganese (mg g^{-1} dry weight).

c. CH-2: iron : manganese ratio.


(a)
mg · g⁻¹
depth
(m)
0
40
0
1
2
3
4
Fe
(b)
mg · g⁻¹
0
2
Mn
(c)
CH-2
0
30
60
Fe : Mn ratio

there was a peak at 350cm and a trough around 325cm, where manganese peaked while iron was still rising. Above 50cm there were indications of a slight decline and the surface sample had the lowest ratio.

In the northeast basin iron (fig. 15a) was found in greater quantities near the base of the core than further up, as in the main basin. However the upper region of relatively depressed values comprised a greater proportion of the core, extending down to 3m. Throughout this upper 3m there was little variation in iron. In the remainder of the core there was a narrow peak around 440cm, a decline to 420cm and then a broad expansion up to 300cm.

The manganese profile in the northeast basin (fig. 15b) did not display any marked division between the upper and lower parts. There were broad peaks around 415,300 and 175cm, with intervening shallow troughs. Above this there was a slow but steady decline to 20cm, where there was a slight peak.

Despite the fairly even patterns of iron and manganese, there was sufficient variability to create a very irregular profile in the iron : manganese ratio below 350cm in NH-1 (fig. 16). There were sharp peaks at 445, 395, 365 and 345cm, as well as a number of less pronounced peaks. Above this the ratio was more constant and lower, although values rose around 250cm. From 165cm the ratio generally rose to a maximum between 80 and 30cm. Above 30cm the ratio again fell.

h. Sulphate

Sulphate levels were very irregular. In CH-2 (fig. 17a) there was a general increase in younger sediments. From a low basal level there was a rapid increase to a narrow peak at 373cm, then a decline

Figure 15.

a. NH-1: iron (mg g^{-1} dry weight).

b. NH-1: manganese (mg g^{-1} dry weight).

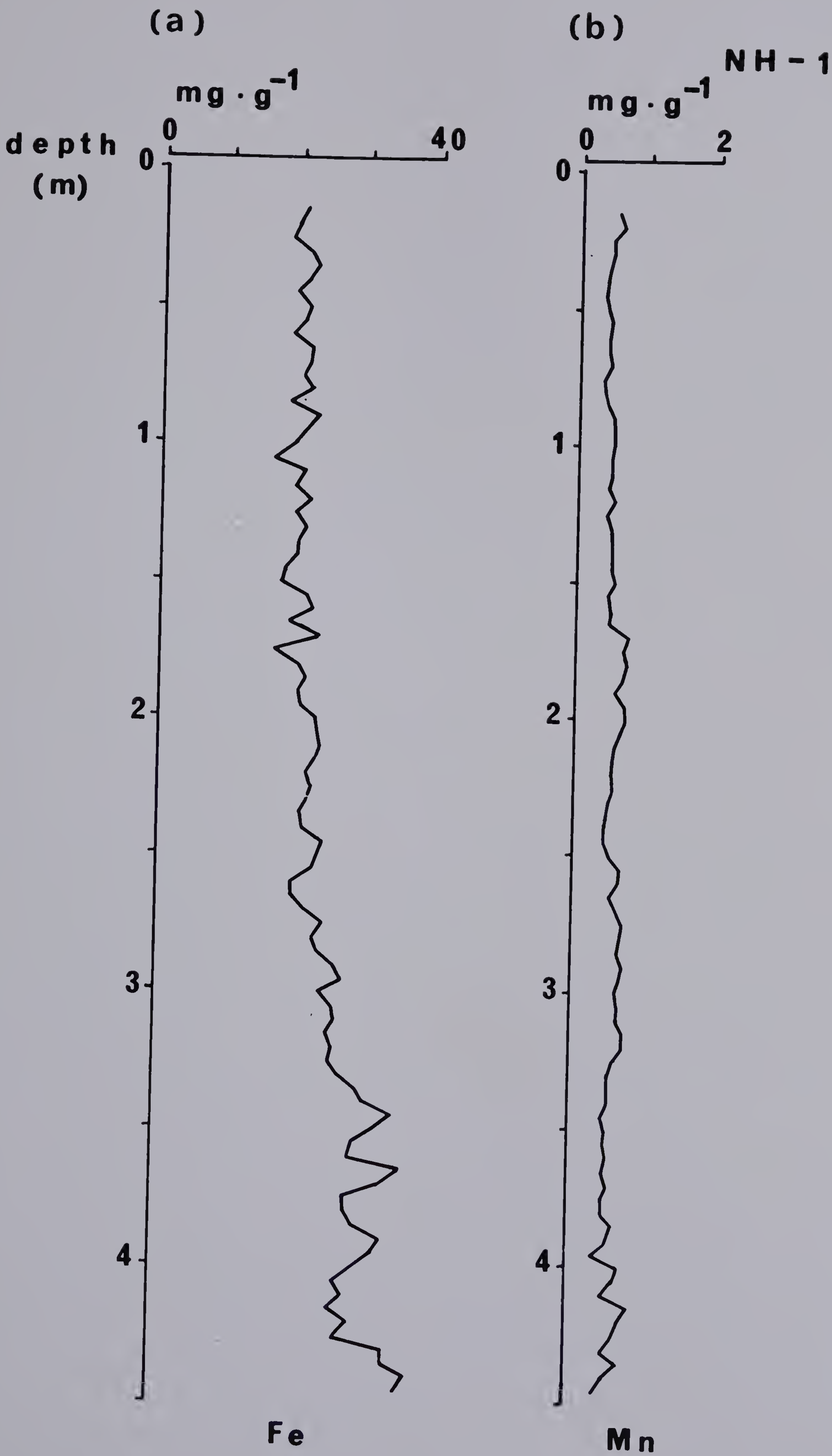
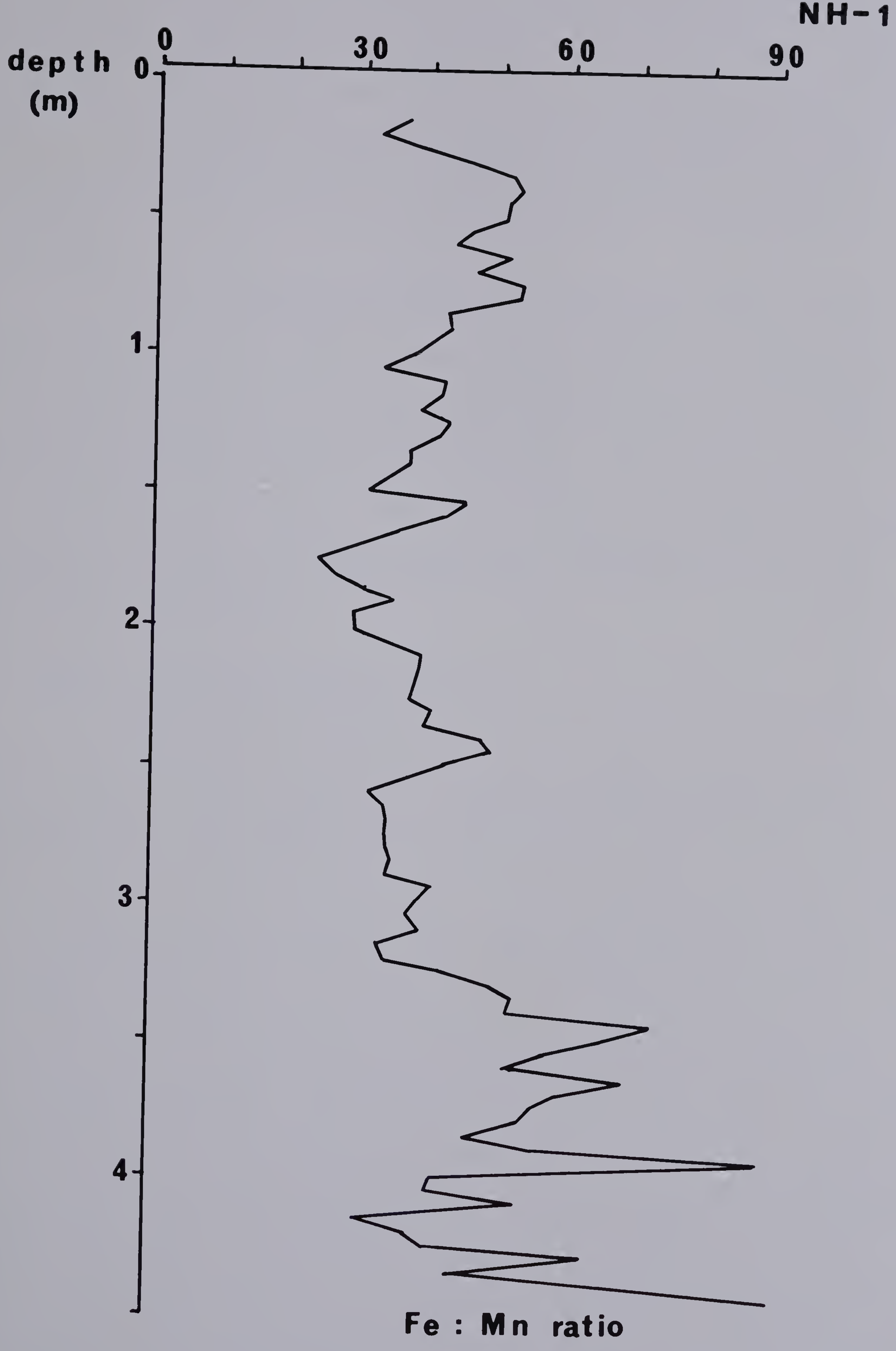

(a)
(b)
NH - 1
mg · g⁻¹
mg · g⁻¹
depth
(m)
0
40
0
2
0
1
2
3
4
0
1
2
3
4
Fe
Mn

Figure 16.

NH-1: iron : manganese ratio


NH-1
depth (m)
0
1
2
3
4
0
30
60
90
Fe : Mn ratio

to lower values between 363 and 353cm. Another peak at 323cm was followed by a more significant trough with a minimum at 290cm. Another sharp peak lay immediately above this, with the next depression around 240cm. From here there was little departure from a pattern of slowly increasing values, apart from an apparently anomolously low sample at 145cm.

In the northeast basin (fig. 17b) there was also a general rise in sulphate up the core. A sharp peak at 410cm was followed by relatively depressed values up to around 325cm. From here the slow trend of increasing sulphate was established. The series of peaks at 315, 275, 240, 210, 195, 165, 135, 90, 75, 40 and 15cm, with intervening troughs, may represent a cyclic phenomenon, although there was a lot of noise in the profile.

i. Sodium, potassium, magnesium and zinc

Sodium declined slowly but steadily up the core in CH-2 (fig. 18a). The only break in this was a slight depression around 350cm. Potassium (fig. 18b) displayed the split between upper and lower portions of the core in common with some other elements. In the lower half there was a narrow depression around 350cm. Above this there was a broad expansion, with a peak around 300cm. The upper 2m of the core had generally lower but steadier results, although from 110 to 50cm there was a broad depression. The profile of magnesium (fig. 18c) in the main basin had rather high values right at the base, particularly at 378cm. Directly above this they were lower, but tended to increase to a peak at 343cm, followed by a decline and increase to a further peak at 295cm. This was repeated and there was another peak at 225cm. Above this there was a slow but fairly steady decline towards the surface. The

Figure 17.

a. CH-2: sulphate (mg g^{-1} dry weight).

b. NH-1: sulphate (mg g^{-1} dry weight).

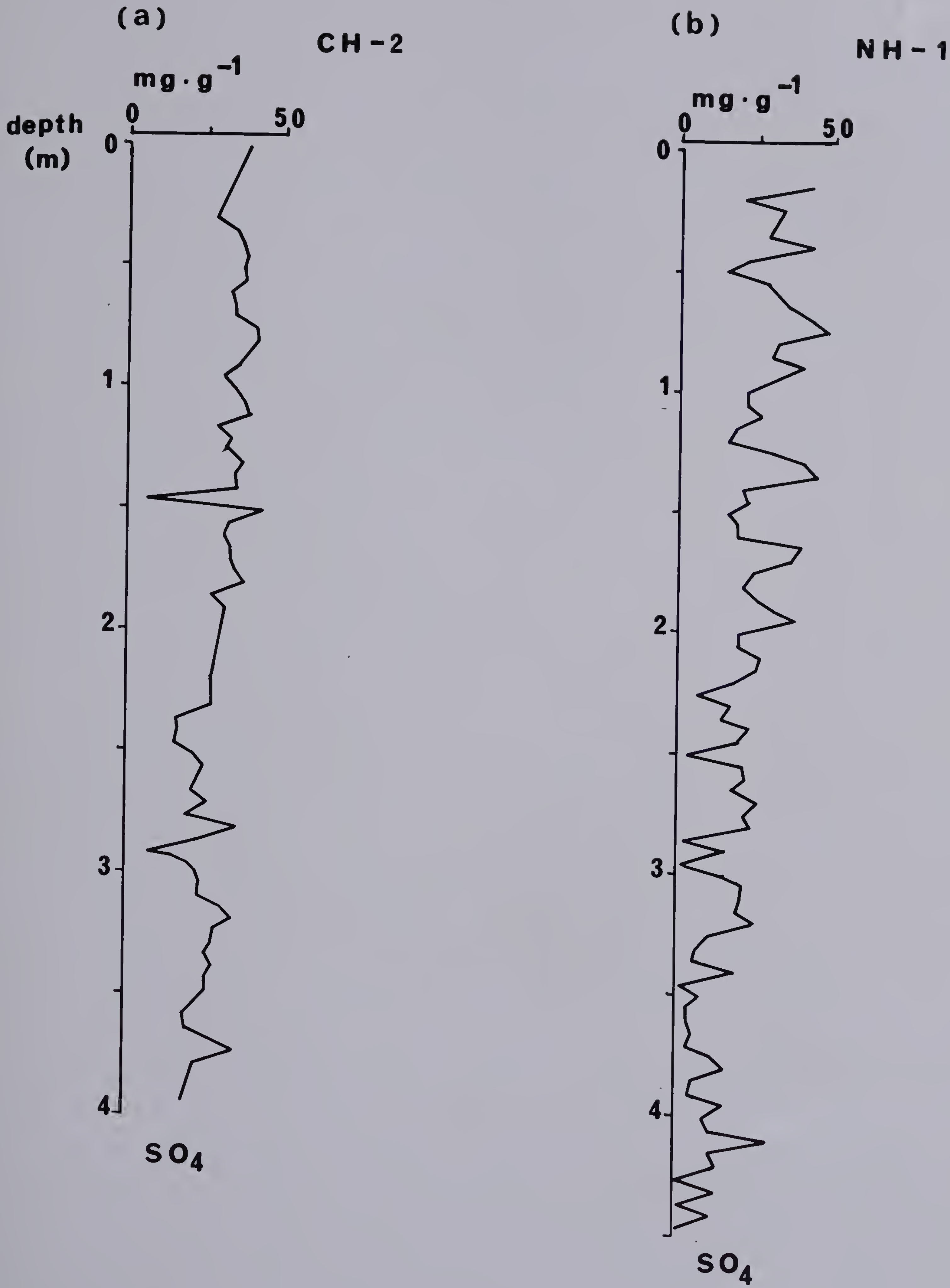

(a)
CH-2
mg · g^{-1}
depth
(m)
0
50
0
1
2
3
4
SO$_4$
(b)
NH-1
mg · g^{-1}
0
50
0
1
2
3
4
SO$_4$

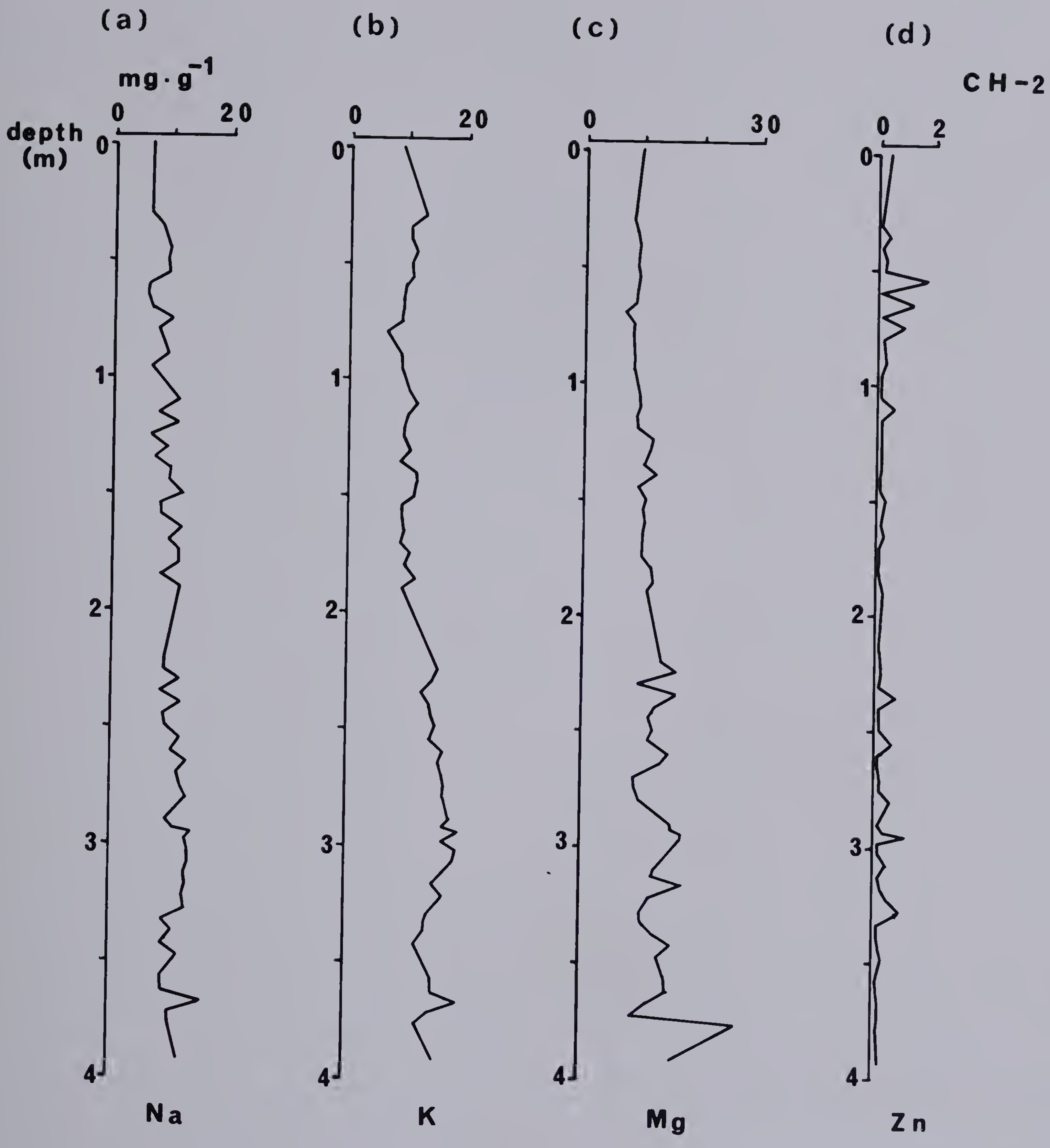
Figure 18.

a. CH-2: sodium (mg g^{-1} dry weight).

b. CH-2: potassium (mg g^{-1} dry weight).

c. CH-2: magnesium (mg g^{-1} dry weight).

d. CH-2: zinc (mg g^{-1} dry weight).



(a)
(b)
(c)
(d)
CH-2
mg · g^{-1}
depth (m)
0
20
30
2
1
3
4
Na
K
Mg
Zn

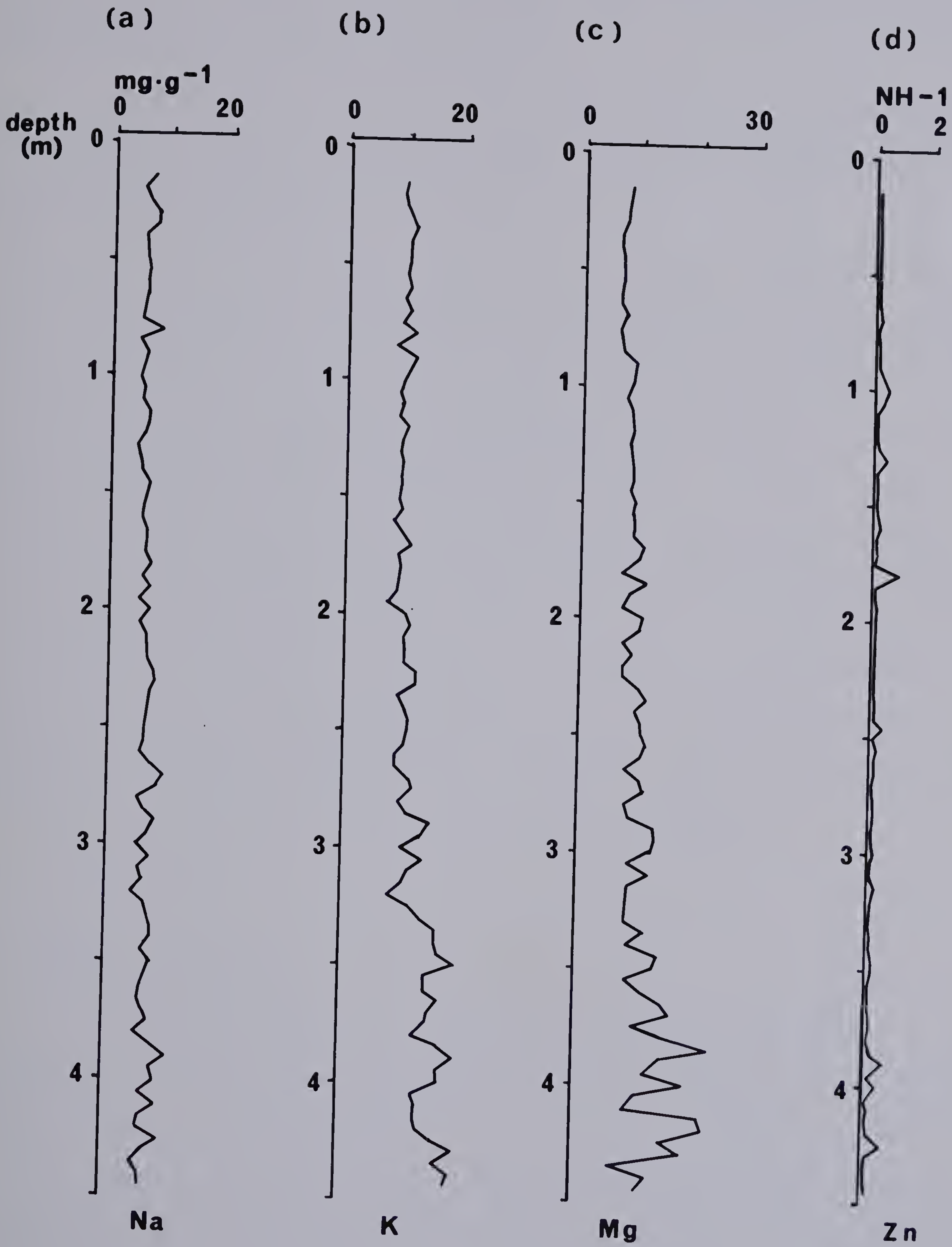
Figure 19.

a. NH-1: sodium (mg g^{-1} dry weight).

b. NH-1: potassium (mg g^{-1} dry weight).

c. NH-1: magnesium (mg g^{-1} dry weight).

d. NH-1: zinc (mg g^{-1} dry weight).


(a)
(b)
(c)
(d)
mg·g⁻¹
NH-1
depth
(m)
0
20
0
20
0
30
0
2
0
1
2
3
4
Na
K
Mg
Zn

pattern of zinc in the main basin (fig. 18d) was relatively even, though interrupted at points by sharp increases. The most significant of these peaks were at 327, 295, 75, 65 and 55cm.

The profile of sodium in NH-1 (fig. 19a) was very even, with a very subtle decline towards the surface. The major irregularities were a number of small peaks near the base, at 425, 410 and 390cm. Potassium (fig. 19b) was a little more irregular near the base. There were fairly major peaks around 430, 390 and 350cm, with intervening troughs. There was a significant minimum at 320cm. Above 300cm the profile showed little variability, although it is noteworthy that almost all of the minor peaks and depressions in the potassium profile were matched by sodium. Magnesium levels (fig. 19c) rose from the base to a broad area of high values from around 430 to 375cm. Above this there was a general tendency to decrease slowly with very little variation. As in the main basin, NH-1 had a very even zinc profile (fig. 19d), apart from sharp peaks evident at 425, 390, 180 and 100cm. Disregarding these peaks, there was a very slight decrease in zinc in the younger sediments.

2. Lac Ste. Anne

a. Physical structure

LSA-1 and LSA-2 were virtually identical in stratigraphy (fig. 3). Virtually the entire organic sediment consisted of a homogeneous marly gyttja of greyish olive colour (5Y 4/2). There was some faint bedding between 168 and 180 cm depth (LSA-2) and slight mottling throughout. At the base there was a sharp transition to heavy grey clay. Lying on this clay base was a thin band of sand grains, whose angular nature indicates aquatic rather than aeolian transport (Emerson 1977).

A decreasing number of sand grains occurred above this band through an interval of 2.1cm and the silt content was somewhat enhanced for approximately 12cm above the clay-organics transition. The two cores differed in that the clay boundary lay at 190.2cm in LSA-1 and at 195.7cm in LSA-2. Structurally they were identical however. Gastropod shells were fairly numerous throughout.

b. Chronology

The basal date of the core indicated that the organic sediments represented a history of over 5630±125 ^{14}C years. The second date, midway up the core was 3360±114 ^{14}C years BP (table IV).

	DEPTH	RADIOCARBON DATE
LSA-1	93.5cm	3360±114 ^{14}C years BP
	184.0cm	5630±125 ^{14}C years BP

Table IV. Radiocarbon ages of sediment samples from Lac Ste. Anne

c. Water content, organic matter, nitrogen and phosphorus

Throughout the organic sediments the water content and organic matter (fig. 20a) were essentially constant. Both dropped sharply at the clay boundary (190cm). Water content remained close to 75% wet weight throughout, with a very slight increasing trend up the core. The water content at 190cm was less than 25% however. The amount of organic matter in the basal clay was less than 4% dry weight, while throughout the remainder of the core it ranged between 15 and 20%, with a slight depression around 160cm and a more significant drop at 100 and 95cm.

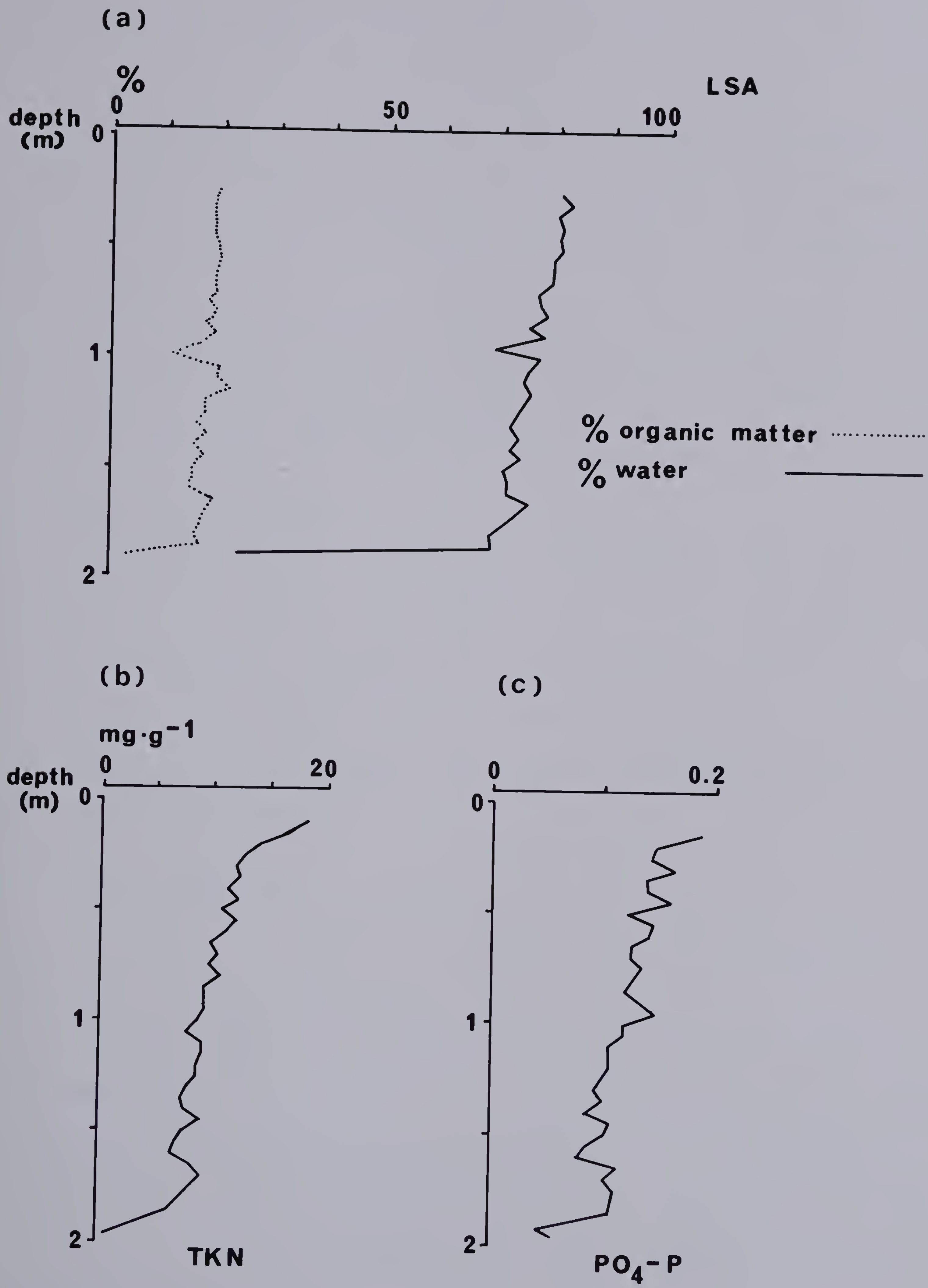
Nitrogen (TKN) and phosphorus (fig. 20b, c) were both very low in the basal clay. In the organic sediments levels were

Figure 20.

a. LSA: % organic matter (as % of dry weight) and % water content (as % of wet weight).

b. LSA: total Kjeldahl nitrogen (mg g^{-1} dry weight).

c. LSA: total phosphorus as PO_4 - P (µg g^{-1} dry weight).


(a)
%
LSA
depth (m)
0
50
100
1
2
% organic matter
% water
(b)
mg·g⁻¹
depth (m)
0
20
1
2
TKN
(c)
0
0.2
1
2
PO4-P

higher and both elements increased steadily up the core. Phosphorus declined slightly in the sand relative to the clay.

d. Total a pigments and total carotenoids

TaP levels were virtually constant throughout the core (fig. 21a). Because the amount of organic matter also showed little change, TaP retained this profile when expressed on a g^{-1} organic matter basis (fig. 21b).

TC (fig. 21c) showed a very slight decreasing trend up the core. The profile was again very consistent. When expressed in terms of organic matter (fig. 21d) there was very little change.

e. Calcium and carbonates

The profiles of calcium and inorganic carbon (fig. 22a) were very similar. Low levels in the basal clay rose abruptly to very high values in the organic sediments. These were fairly consistent up to approximately 135cm where they began to decline. This trend continued to the surface of the sediments. There was a minor trough at 50cm and a minor peak at 35cm.

f. Iron and manganese

The profiles of iron and manganese (fig. 22b, c) were quite even, with little internal noise.

Basal samples had somewhat enhanced levels of iron, although the sample in the sand layer was low. From 175cm iron was fairly constant up to 125cm, where a slow trend of increasing levels began, peaking at around 55cm. There was a slight break in this trend around 90cm, at which point there was a slight decline. Above the 55cm level iron gradually eased off again.

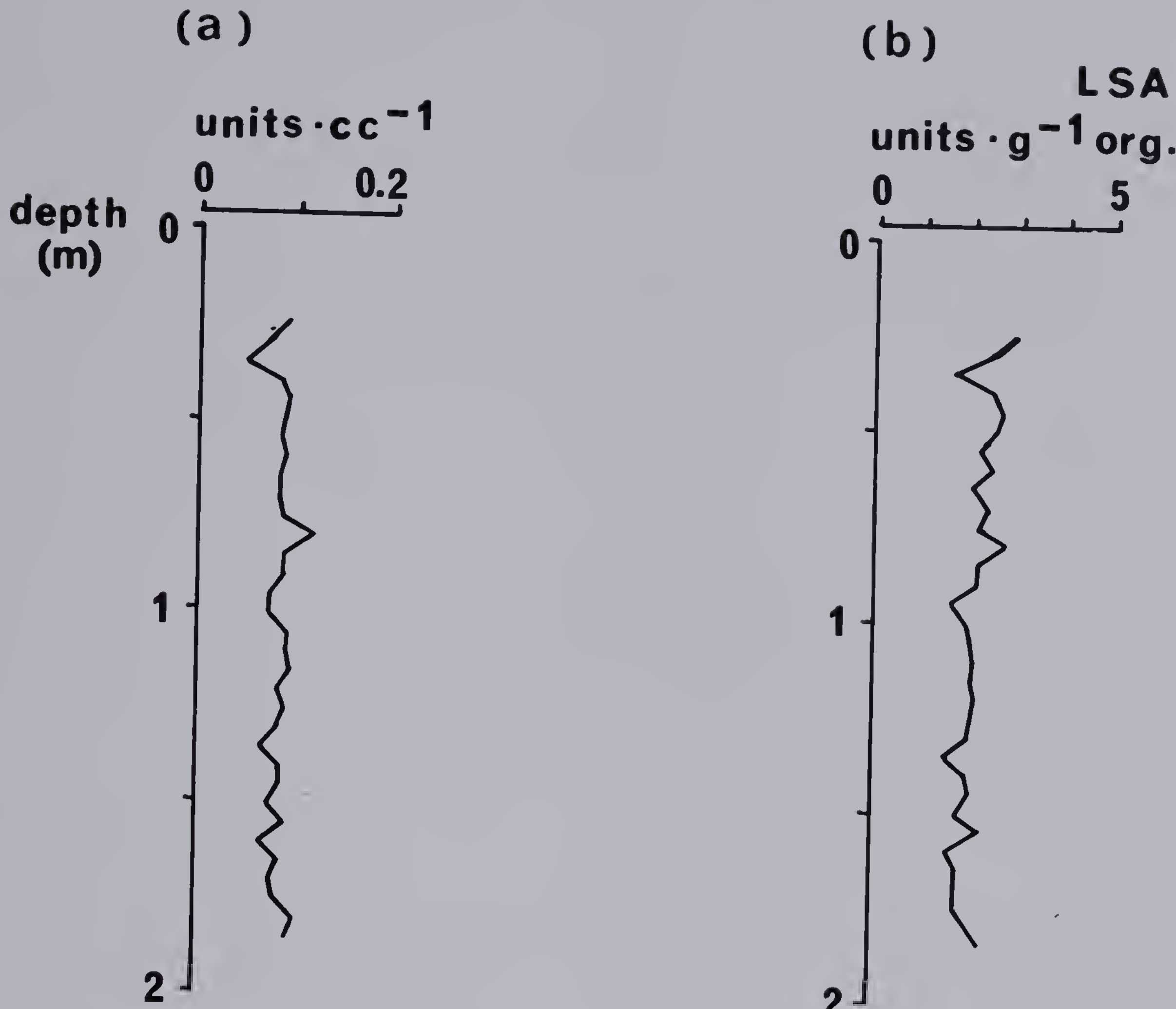
Figure 21.

a. LSA: total a pigments (SCDP units cc^{-1} wet sediment).

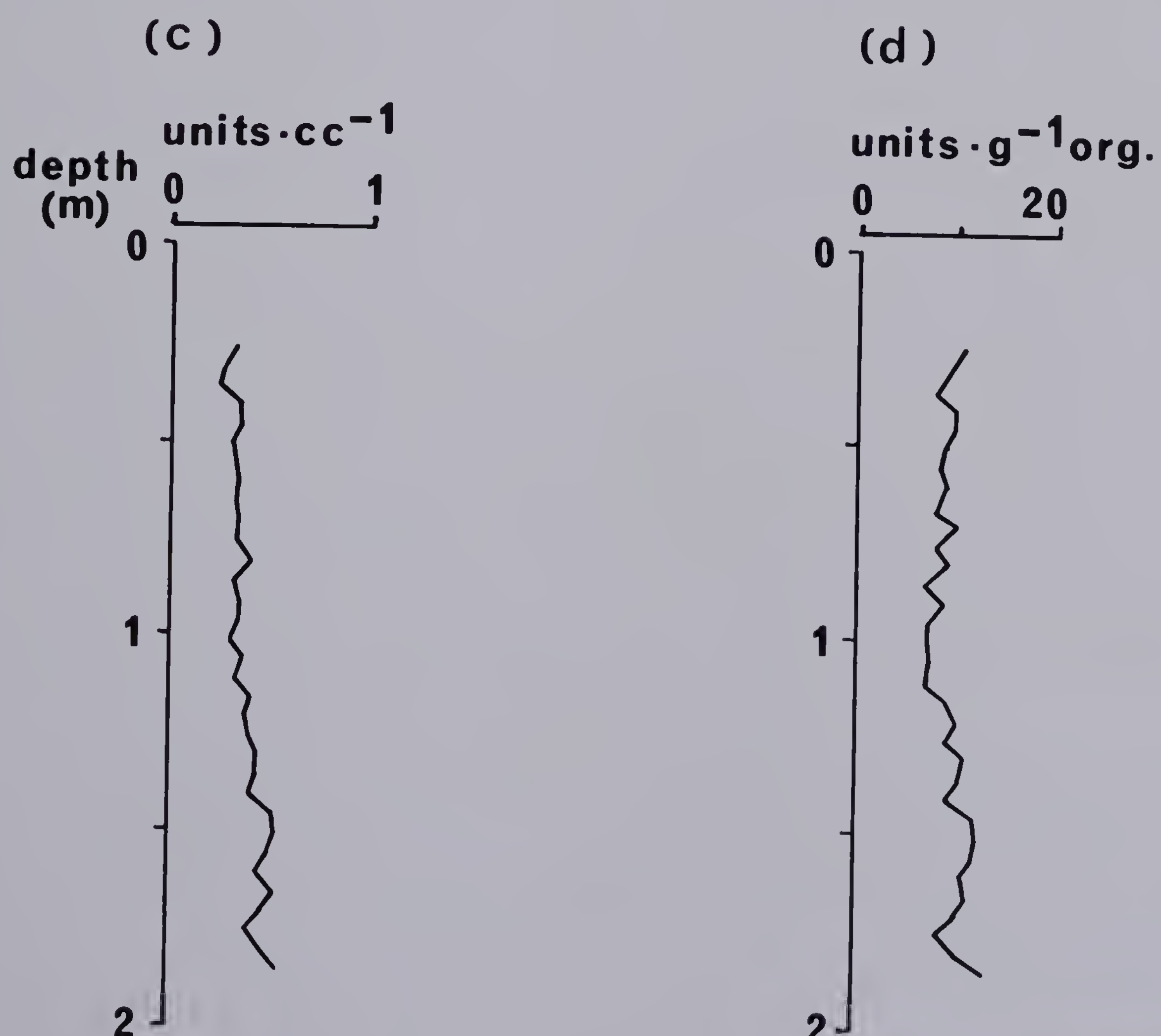
b. LSA: total a pigments (SCDP units g^{-1} organic matter).

c. LSA: total carotenoids (units cc^{-1} wet sediment).

d. LSA: total carotenoids (units g^{-1} organic matter).


(a)
units·cc⁻¹
0
0.2
depth (m)
0
1
2
(b)
LSA
units·g⁻¹ org.
0
5
0
1
2

TaP


(c)
units·cc⁻¹
depth (m)
0
1
0
1
2
(d)
units·g⁻¹org.
0
20
0
1
2

TC

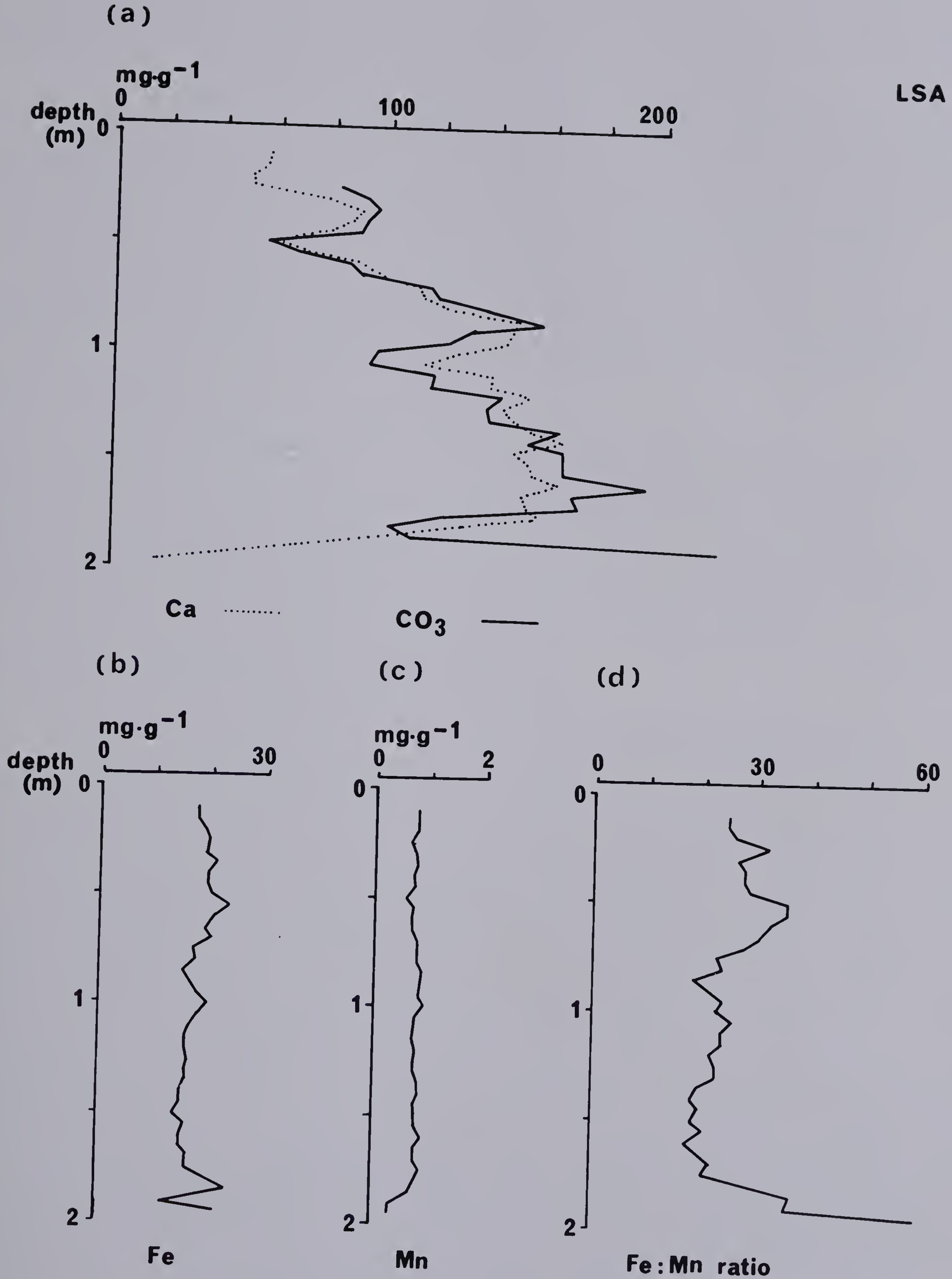
Figure 22.

a. LSA: calcium and carbonates (both in mg g^{-1} dry weight).

b. LSA: iron (mg g^{-1} dry weight).

c. LSA: manganese (mg g^{-1} dry weight).

d. LSA: iron : manganese ratio.


(a)
mg·g⁻¹
0
100
200
depth (m)
0
1
2
LSA
Ca
CO3
(b)
mg·g⁻¹
0
30
depth (m)
0
1
2
Fe
(c)
mg·g⁻¹
0
2
0
1
2
Mn
(d)
0
30
60
0
1
2
Fe : Mn ratio

Apart from the basal samples in clay and sand, where it was in low concentrations, manganese was fairly constant throughout the core. There was a broad shallow trough from around 100 to 35cm.

Because of the high iron content and low manganese, the iron : manganese ratio (fig. 22d) in the basal samples was very high. Throughout the remainder of the core the ratio was lower in general. However, because of the increasing trend of iron through the middle of the core there was a corresponding increase in the ratio, peaking around 50cm.

g. Sulphate

The sulphate profile (fig. 23a) was quite unique in Lac Ste. Anne. Throughout most of the core there was very little present. However, the block of samples between 95 and 55cm had enhanced values, forming twin peaks at these extremes with a trough between.

h. Sodium, potassium, magnesium and zinc

These components (fig. 23b, c, d, e) showed very little change during the period represented by the organic sediments. The basal clay was relatively deficient in magnesium and the remainder of the core displayed a very slight declining trend. In contrast, sodium increased very slightly up the core, with levels in the basal clay consistent with those in the rest of the core. Potassium displayed a very slight deficit in the sandy layer. There was a slight declining trend up to 165cm whence levels rose slowly to peak at 50cm. Above this potassium content was slightly lower, but fairly steady. Zinc was generally very stable throughout, with minor increases at 155 and 145cm, and larger peaks at 100 and 35cm.

Figure 23.

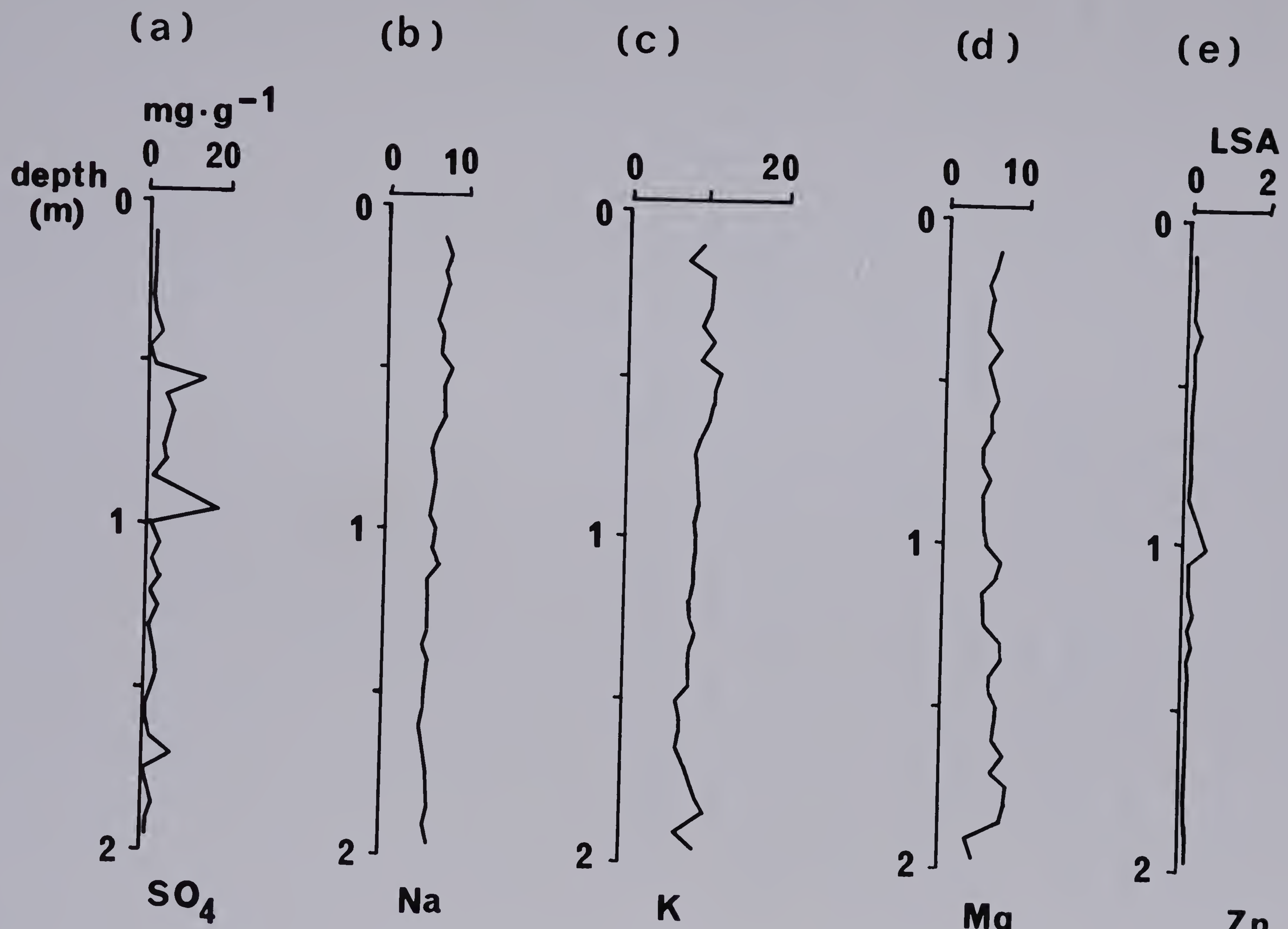
a. LSA: sulphate (mg g^{-1} dry weight).

b. LSA: sodium (mg g^{-1} dry weight).

c. LSA: potassium (mg g^{-1} dry weight).

d. LSA: magnesium (mg g^{-1} dry weight).

e. LSA: zinc (mg g^{-1} dry weight).



(a)
(b)
(c)
(d)
(e)
mg·g⁻¹
LSA
depth (m)
0
20
10
2
1
SO4
Na
K
Mg
Zn

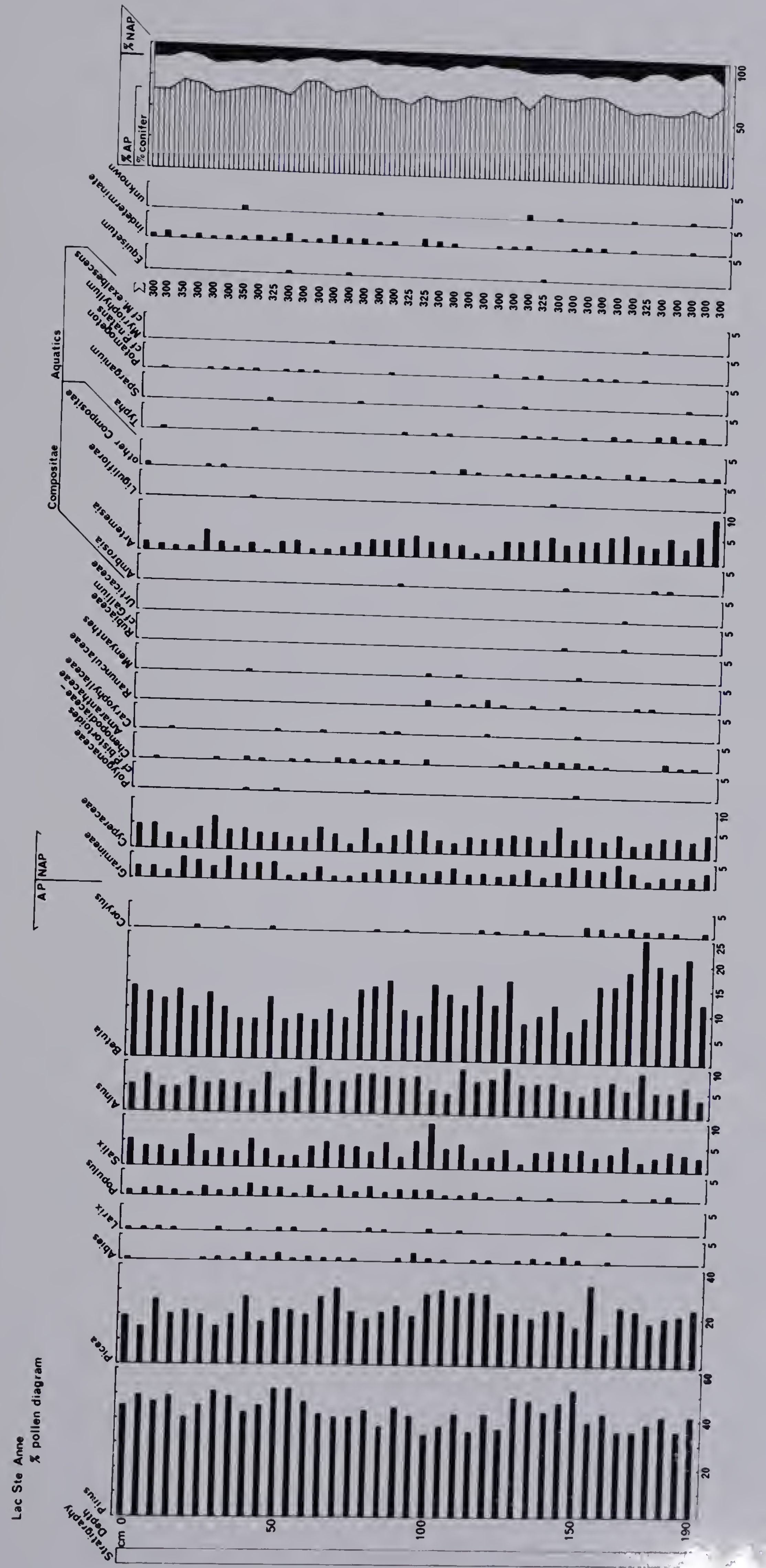
i. Pollen

The pollen record in the Lac Ste. Anne core showed little change over time (fig. 24). The ratio of arboreal to non-arboreal pollen remained effectively constant and high throughout, as did the proportion of coniferous pollen. The only components worth remarking upon are Populus, Betula and Artemesia. Rare throughout, poplar was particularly so in the lower third of the core, where there was a corresponding rise in Artemesia. There was a distinct peak in birch around 170cm. Above and below this there were only minor fluctuations.

Pollen from aquatic macrophytes was extremely rare throughout, apart from the Cyperaceae, which almost certainly contained a fairly high proportion of Scirpus pollen. This genus forms a major component of the weed beds around the lake margin. The only aquatic whose profile showed any change was Typha. This occurred consistently in the lower half of the core, though at very low percentages. Further up it was found only sporadically.

Figure 24.

LSA: percentage pollen diagram.


Lac Ste Anne
% pollen diagram
Stratigraphy
Depth
cm
Pinus
Picea
Abies
Larix
Populus
Salix
Alnus
Betula
Corylus
AP
NAP
Gramineae
Cyperaceae
Polygonaceae
cf Bistortoides
Chenopodiaceae-Amaranthaceae
Caryophyllaceae
Ranunculaceae
Menyanthes
Rubiaceae cf Galium
Urticaceae
Ambrosia
Artemesia
Liguliflorae
other Compositae
Compositae
Typha
Sparganium
Potamogeton cf P. natans
Myriophyllum cf M. exalbescens
Aquatics
Σ
Equisetum
indeterminate
unknown
% AP
% conifer
% NAP

DISCUSSION

1. Resolution

The sediments of Hastings Lake and Lac Ste. Anne are subject to considerable resuspension, since both lakes are shallow and lack summer thermal stratification. This tends to mask short term variations in sedimentary influx of elements. The depth to which this disturbance extends is difficult to assess. By close sampling and analysis of orthophosphate and ammonia - nitrogen in the surface sediments of Lake George in Uganda, Viner (1977) was able to estimate regular disturbance down to 5cm, with less frequent disturbance down to approximately 20cm. The degree of turbulent mixing is strongly dependent upon lake morphometry and degree of exposure.

The presence of sharp peaks, for example in the profiles of zinc, suggests that the depth of mixing is less than 5cm in both Hastings Lake and Lac Ste. Anne. Certainly it does not exceed 15cm, as there are a number of cases of unequivocal peaks where levels rise on either side of the maximum. An example of this is the increase in zinc on either side of 330cm in CH-2.

In Lac Ste. Anne the presence of sand grains 2cm above the bed of sand lying on the basal clay suggests that this was the depth to which large - scale disturbance was taking place at that time in the lake's history.

The very fine bands of carbonate and red material in CH-1 and CH-2, in some cases less than 1mm thick, imply that disturbance may have been minimal at certain times.

This suggests that minor periods of enhanced production,

indicated by a number of components near the base of CH-2, for example, are real. However, in general interpretations have been restricted to long-term trends established by consistent changes in sedimentary components.

2. Sedimentation

The radiocarbon dates indicate that organic sedimentation commenced at approximately 4780 BP in the main basin of Hastings Lake, while in the northeast basin it started circa 3890 BP. In Lac Ste. Anne organic influx began about 5630 BP. These dates suggest that these basins acquired standing water towards the end of the Hypsithermal Period that has been indicated by a number of studies in the area (Klarer and Hickman 1978, Lichti-Federovich 1970). Presumably as the climate became cooler and wetter, evaporation rates declined and the basins became occupied by water. There is no evidence for any stratigraphic discontinuity above the basal dates. This indicates that the lakes have not dried since.

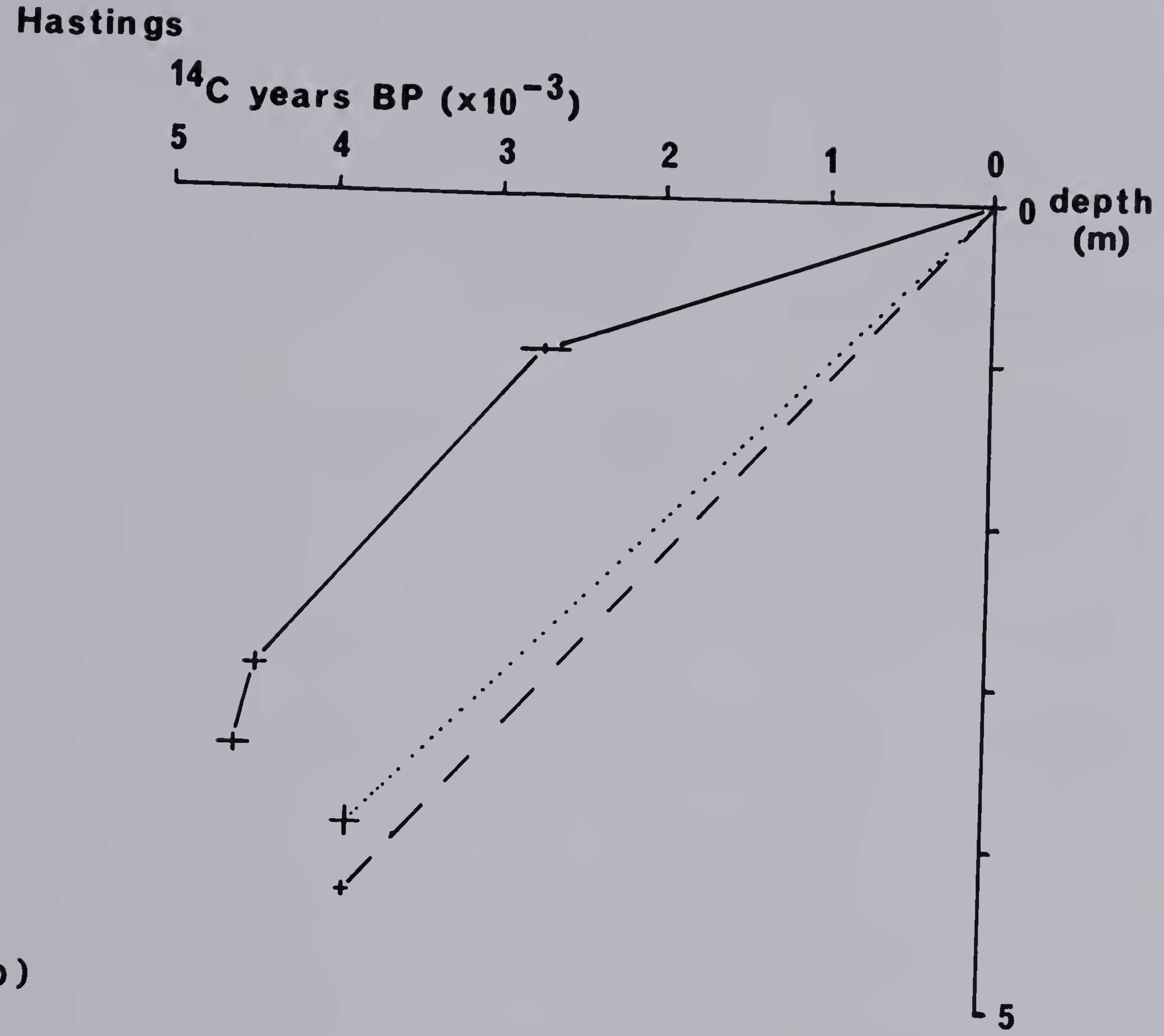
The origin of the heavy grey clays has not been established, although visually they correspond to typical immediate postglacial, erosional deposits (Mackereth 1966). It is possible that during the dry phase previous deposits of organic sediment were eroded away by aeolian activity. On the other hand, the clays may represent a rapid redeposition phase resulting from shoreline erosion as the basins filled (Hecky 1975). However the band of sand lying on the clay in LSA, as well as the fine sand just above the boundary in CH-1, are more likely examples of this.

The pattern of dates from CH-1 (fig. 25) indicates an initial phase of relatively rapid deposition. From 4580 to 4450 BP the mean

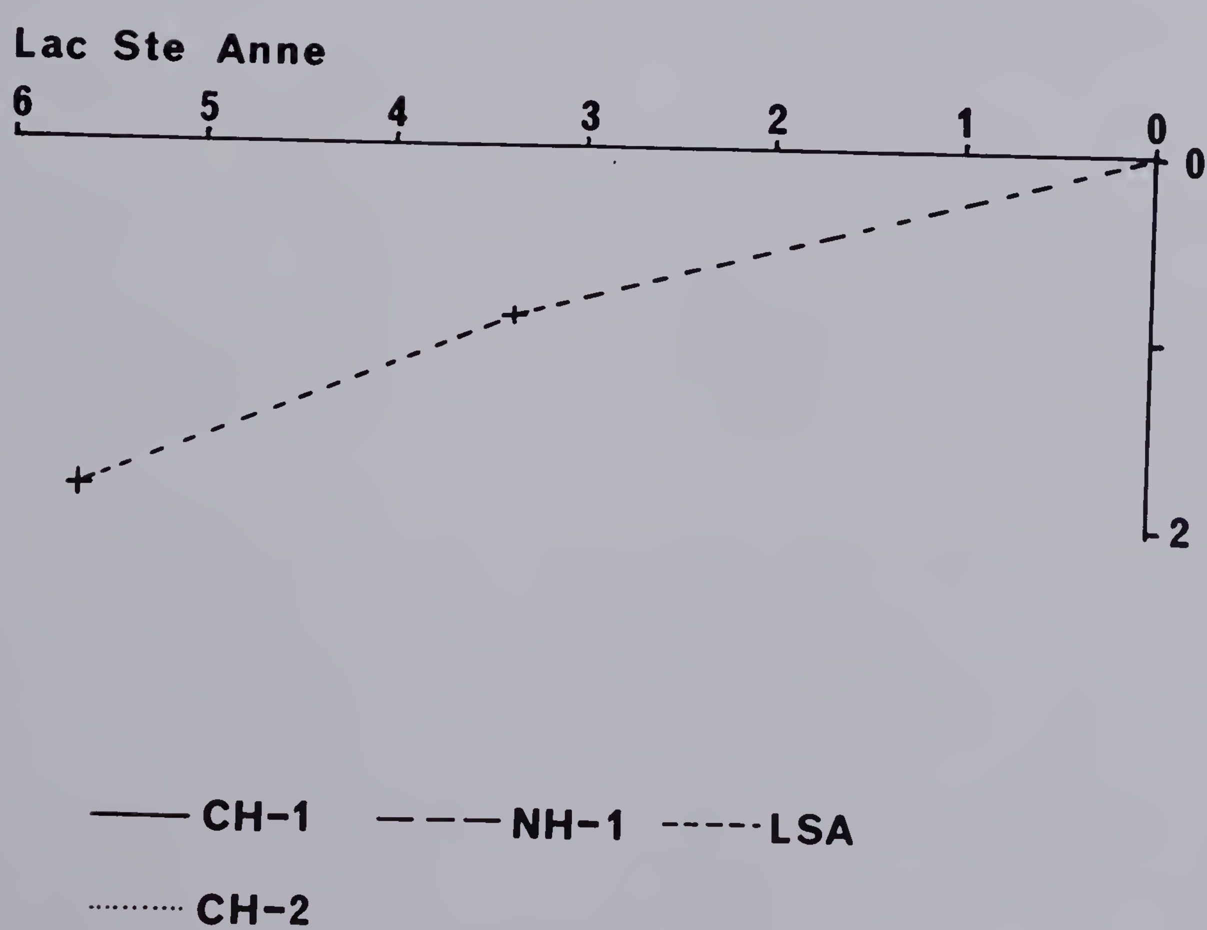
Figure 25.

Chronology and sedimentation rates for all cores.

(a)


Hastings
^{14}C years BP (x10^{-3})
5
4
3
2
1
0
0 depth (m)
5

(b)


Lac Ste Anne
6
5
4
3
2
1
0
0
2
CH-1
NH-1
LSA
CH-2

deposition rate was 3.85mm yr^{-1}. This declined to 1.14mm yr^{-1} over the next 1740 years and further dropped to 0.36mm yr^{-1} from 2710 BP to the present. The mean deposition rate over the entire period was 0.75mm yr^{-1}. While basal sediments in the northeast basin are about 900 years younger, the mean deposition rate here was considerably higher at 1.11mm yr^{-1}. This represents a greater influx of material, largely contributed by organic matter.

A direct interpretation of initially high deposition rates as an indication of high influx on the basis of lake surface area must be considered with caution. Based upon the ratio of mean depth to maximum depth and a graphical comparison of actual to theoretical values of volumes in successive depth strata, both the main basin and northeast basin of Hastings Lake conform most closely to a hyperbolic shape (Lehman 1975). This introduces a considerable degree of focusing, which tends to amplify the deposition rate in the centre of the basin relative to overall influx. This is particularly so in the early depositional phases (Lehman 1975).

The dates from Lac Ste. Anne indicate little change in the deposition rate. In the initial phase it averaged 0.40mm yr^{-1}. After 3360 BP it was somewhat lower at 0.28mm yr^{-1}. The mean over the entire period was 0.38mm yr^{-1}, less than half that in the main basin of Hastings Lake.

The mean depth to maximum depth ratio and the distribution of volume with depth indicates that Lac Ste. Anne conforms most closely to an ellipsoid in basin form. This creates little distortion of deposition rate as a reflection of areal influx over the depositional history (Lehman 1975).

3. Indicators of erosion

Magnesium, sodium and potassium are primarily associated with the mineral components of the sediment and are reasonable indices of the input of terrigenous material to the lake (Mackereth 1966). The low mineral content of Hastings Lake relative to the organic content implies that erosion has never been intense. This is consistent with the small basin and low relief. The profiles of magnesium, sodium and potassium do indicate that erosion was somewhat more intense earlier in the lake's history than later. In CH-2 the decline was most evident between 250 and 200cm, which also corresponds to the rather abrupt increase in productivity indices. In the northeast basin the decline of the mineral components was more abrupt and occurred somewhat deeper in the core, between 350 and 300cm. This probably corresponds chronologically to the reduction of erosion in the main basin.

If lake levels have increased since then, the rise must have been slow. Otherwise a large input of inorganic material from shoreline erosion would have occurred (Hecky 1975). The more irregular profile near the bases of the cores suggests a greater instability in lake elevations. It is of note that sections from the centre of Hastings Lake characterized by sandy inclusions, alternative indicators of erosion, are near the base and just below 250cm.

Lac Ste. Anne appears to have had an essentially constant influx of terrigenous material since soon after organic sedimentation began. The sand layer indicates shoreline erosion. The depression of the concentration of some components in this layer is most likely a function of grain size distribution (Loring 1976) rather than the result of lower influx rates.

4. Late Holocene vegetation around Lac Ste. Anne

The pollen analysis suggests a slight shift in vegetation during the early stages. Poplar pollen is poorly preserved (Ritchie 1976). Here, despite its overwhelming dominance among the present-day vegetation, it forms such a small proportion of the pollen sum that little weight can be placed on its apparent greater rarity early on. More significant are the relatively high values for Betula and Artemesia, which suggests a somewhat drier climate and more open forest. There appears to have been a slight shift southeastward in the boreal-cordilleran ecotone and, when the original organic sediments were laid down, Lac Ste. Anne was probably surrounded by a more typically parkland vegetation. This is consistent with the southward shift of the boreal forest noted by Ritchie (1976) across the western interior.

5. Indicators of productivity

a. Organic matter

The loss on ignition measures, with insignificant interference (Konrad et al. 1970), the influx of organic matter to the sediments. It therefore represents a generalized history of productivity within the lake, assuming that the influx of allochthonous organic matter has been negligible or constant. In the main basin of Hastings Lake organic matter values suggest that production was initially very low, but increased to peak about 340cm. It then declined somewhat for a short period of time. Since this it has generally increased until near recent times. From 50cm depth upwards there has been a slight decline. There was also a slight break in the increasing trend at about 100cm depth.

In the northeast basin too there was an early, small peak in organic influx. There was then a decline, followed by a fairly even

increase up until near recent times. The slight decline in productivity evident in CH-1 is also apparent here.

The generally higher organic matter values for the northeast basin do not necessarily reflect greater productivity. They may result from a lower influx of inorganic constituents due to the smaller basin, a greater influence of surrounding terrestrial vegetation in the form of litter input, or better preservation.

Organic matter from Lac Ste. Anne suggests an extremely even level of organic input after the initially low values in the basal clay. Overall there is a very slight increase apparent throughout the core, but no significant irregularities.

b. Calcium and carbonates

i. Calcium and inorganic carbon in the water column

In freshwater inorganic carbon is largely distributed between dissolved carbon dioxide (CO_2), carbonic acid (H_2CO_3), bicarbonate (HCO_3^-) and carbonate ($CO_3^=$) ions. Equilibrium is maintained according to the following relationships (Wetzel 1975):

$$(1)\quad HCO_3^- + H_2O \Longleftrightarrow H_2CO_3 + OH^- \qquad 8 < pH < 9.5$$

$$(2)\quad CO_3^= + H_2O \Longleftrightarrow HCO_3^- + OH^- \qquad pH > 9.5$$

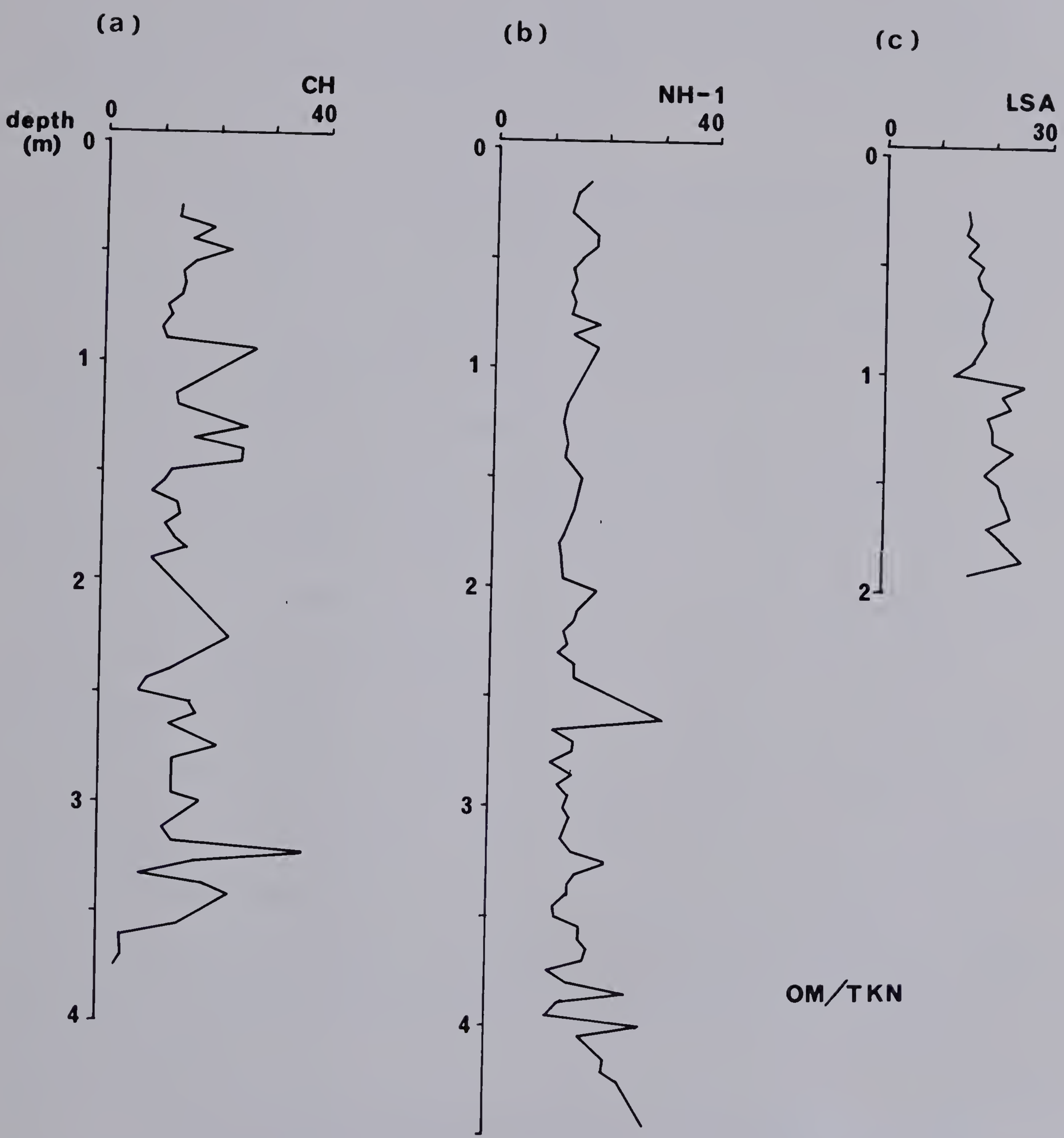
$$(3)\quad H_2CO_3 \Longleftrightarrow H_2O + CO_2 \qquad pH < 8$$

Bicarbonate - rich water, such as in Hastings Lake and Lac Ste. Anne, is strongly buffered with respect to pH. Neutralization of hydroxyl ions by added hydrogen ions is immediately followed by a shift to the right in equation (2). A shift to the left in equation (2) upon addition of hydroxyl ions acts immediately to restore equilibrium.

The addition of calcium to lake water is primarily effected

Figure 26.

Organic matter : total Kjeldahl nitrogen ratios for all basins.


(a)
CH
depth (m)
0
40
0
1
2
3
4
(b)
NH-1
0
40
0
1
2
3
4
(c)
LSA
0
30
0
1
2
OM/TKN

by leaching, in contrast to such elements as magnesium, sodium and potassium. Only when erosion is intense is there significant addition of calcium in mineral form. The leaching process is caused by enrichment of ground water in CO_2 derived from plant and microbial respiration, consequent formation of H_2CO_3, and solution of calcium in the form of $Ca(HCO_3)_2$ (Wetzel 1975).

ii. Calcium carbonate precipitation and resolution

Precipitation of carbonate occurs primarily in association with calcium, although magnesium may be involved to a lesser extent. The formation of particulate $CaCO_3$ is controlled chemically by two major factors. First, the removal of CO_2 from the water causes an oversaturation of carbonate via shifts in the above equations. Second, the solubility of CO_2 and $CaCO_3$ is temperature - dependent, decreasing rapidly over the range from 0° to 15°C (Otsuki and Wetzel 1974). In general the former is dominant and there are many examples where photosynthetic removal of CO_2 during peak production coincides with the annual peak of $CaCO_3$ precipitation (Serruya 1976, Otsuki and Wetzel 1974). In particular, Megard (1969) found a direct relationship between calcium depletion and mean daily rates of planktonic carbon assimilation in six lakes. He calculated that approximately one mole of $CaCO_3$ is precipitated for every four moles of carbon assimilated by phytoplankton.

The ability of some macrophytes in particular to utilize bicarbonate directly as a carbon source results in proportionally greater precipitation of $CaCO_3$ by these plants (Wetzel 1960). To a certain extent this may also reflect localized enhancement of temperature, which has been shown to cause $CaCO_3$ precipitation on

artificial macrophyte leaves by reducing its solubility on their surfaces (Dale and Gillespie 1978).

Photosynthetically induced particulate $CaCO_3$ is redissolved in the hypolimnion of stratifying lakes (Megard 1969). Presumably it may also return to solution in non-stratifying lakes when resuspended during periods of lower productivity, such as at night on a diurnal basis, or in winter on a seasonal basis, when CO_2 levels are enhanced. Cooler water temperatures would facilitate this.

It has also been noted that, while submersed macrophytes and microalgae cause a net production of $CaCO_3$, the respiratory production of CO_2 during decomposition of emergent marsh plants and allochthonous organic matter moves the balance in the opposite direction (Felfoldy et al. 1969). Bortleson and Lee (1972) found that the concentration of $CaCO_3$ in marl sediments of Lake Mendota decreased in deep water relative to shallow water. In gyttja overlying the marl the opposite trend was observed. They considered this most likely due to a relative increase in the dilution of carbonate by inorganic materials closer to shore, or to a relative increase in planktonic photosynthesis in deeper water versus shallower following the shift from marl to gyttja sedimentation.

A couple of other factors affect the interpretation of paleoproductivity based upon $CaCO_3$ content of the sediment. Dissolved organic matter has a strong tendency to adsorb to particulate and colloidal carbonate, reducing bacterial metabolism and attendant inorganic and organic regeneration, as well as reducing inorganic carbon dissociation from the carbonate-organic complex (Wetzel 1972). The ability to exist in colloidal form may lead to continuous

super - saturation (Otsuki and Wetzel 1974).

With the above in mind, an interpretation of the distribution of Ca^{++} and $CO_3^{=}$ in the cores from Hastings Lake and Lac Ste. Anne may be made. For productivity the calcium analyses are of more value as this component is less subject to re - solution than is carbonate. In the northeast basin of Hastings and in Lac Ste. Anne there is a strong correlation between calcium and carbonate ($r = 0.683$, $p<0.001$; $r = 0.831$, $p<0.001$ respectively), indicating both that the predominant form of carbonate precipitation has been with calcium and that differential re - solution has been minimal. In the main basin of Hastings the relationship is not significant ($r = 0.308$). This is partly due to the use of different cores for analysis of the two components, but may also reflect a greater degree of differential re - solution. To confuse the picture however, it should be noted that in terms of milliequivalents, calcium levels in Lac Ste. Anne sediments exceed carbonate levels by 2.5 to 3.3 times, whereas in the northeast basin of Hastings Lake they are very close to a one - to - one relationship. This suggests a fairly even, continuous loss of sedimentary carbonate in Lac Ste. Anne.

Calcium levels in both basins of Hastings Lake show an initial early peak, a decline, and a more significant increase. This is consistent with the pattern of organic matter. The increase to the major peak in the main basin is much more abrupt than suggested by organic matter, occurring around 200cm in the core. These high levels stayed fairly constant up to about 90cm. There followed a rather abrupt decline of about 35%, after which calcium levels remained generally stable.

In the northeast basin the major peak of calcium was reached more quickly than for organic matter, at about 320cm. High

levels were maintained up to 150cm depth, whereupon there was a tendency to decline. The extremely low levels of calcium between 80 and 30cm are considerably below the expected values derived from carbonate concentrations. There is no readily available explanation for this deficiency, but it is felt that these samples are of questionable value for interpreting productivity.

The close conformity of calcium profiles in Hastings Lake with those of total a pigments and, to a lesser extent, organic matter, supports the use of these as evidence of paleoproductivity history. In Lac Ste. Anne however both calcium and carbonate had very high levels during the first half of the lake's history, but have steadily declined since. This contrasts sharply to the profiles of any other component analysed. It suggests that while photosynthetic activity may have been the mechanism for initiating the precipitation of $CaCO_3$, some other factor may have been controlling the ultimate levels. This could have been an overall depletion of the glacial tills of calcium and carbonate, or could represent a shift in source of production causing its precipitation.

c. Pigments

The decay of plant matter contributes pigments and their degradation products to the sediments. Changes following permanent burial are fairly minimal (Brown et al. 1977), although diagenetic processes in the water column and surficial sediments are complex. Nevertheless analysis of combined sedimentary pigments and degradation products may provide a generalized summary of productivity history.

Chlorophylls degrade to phaeophytins or to chlorophyllides by the loss of their central magnesium ion or the phytol group

respectively. Loss of both the magnesium ion and the phytol group yields a phaeophorbide. In addition, oxidation of the cyclopentenone ring generates allomerized chlorophyll, which may then pass through the same diagenetic pathways (Brown et al. 1977).

The degradation of carotenoids has received considerably less attention, but their preservation is favoured over chlorophylls in the decay of algal material in lakes (Sanger and Gorham 1972).

With this in mind an interpretation of the total _a_ pigments and total carotenoids profiles may be made. A change in the ratio of one to the other may reflect a change in preservation conditions or may suggest a change in the balance of contributing organisms.

The T_a_P profile from CH-2 conforms very closely to that of calcium, with levels above 200cm some two to three times those below. T_a_P at the base of the core were quite irregular, in some cases below the limits of detection, but they were generally higher than between 300 and 270cm. Here the same depression as in calcium was observed. The T_a_P gradually declined in the upper 80cm, although calcium was fairly constant.

In terms of the distribution of peaks the TC profile in CH-2 closely resembles that of T_a_P. However the peaks in the lower half of the core are extremely exagerated while the upper half of the core does not display particularly enhanced levels of carotenoids. The resultant T_a_P : TC ratio has its highest values in the top metre, somewhat lower levels in the second metre, and quite low values below this. This probably results from a combination of the two factors discussed above. The fact that the T_a_P : TC ratio remains fairly constant within the three sections noted suggests that preservation conditions were of

less importance in generating the final values than a change in the nature of contributing material. Sanger and Gorham (1972) consider that in general inputs of terrestrial organic matter tend to increase the T<u>a</u>P : TC ratio, as carotenoids degrade more rapidly in soils than do chlorophylls. Fogg and Belcher (1961) point out that autumn leaves and, presumably, decaying emergent aquatic macrophytes contain less chlorophyll than carotenoids. This is supported by the data of Sanger and Gorham (1967). Freshly fallen leaves in autumn had a T<u>a</u>P : TC ratio of 0.14; leaves on the soil surface in the spring had a ratio of 0.29; average values of the ratio in the L_1 soil horizon were 1.0. This suggests that the low ratio values near the base of the core may result from a relatively greater direct input of leaf litter in the early history of the lake. Such a direct input would have a greater impact than an indirect input of organic in view of the small basin and low inflow.

The profiles of both T<u>a</u>P and TC in NH-1 are considerably more stable than in CH-2. At the base they are somewhat irregular; they are stable through most of the core and then show a tendency to decline near the surface. The T<u>a</u>P : TC ratio (fig. 27) generally increases up the core, but again the nature of its increase, in jumps rather than an even rise, suggests that changes in contributing material are the predominant controls.

Profiles of T<u>a</u>P and TC from Lac Ste. Anne are very consistent, with just a slight tendency to decline in the carotenoids. This results in an increase in the T<u>a</u>P : TC ratio (fig. 28) in the upper part of the core.

Interpreting these profiles in terms of productivity, it

Figure 27.

Total $\underline{a}$ pigment : total carotenoid ratios for Hastings Lake.

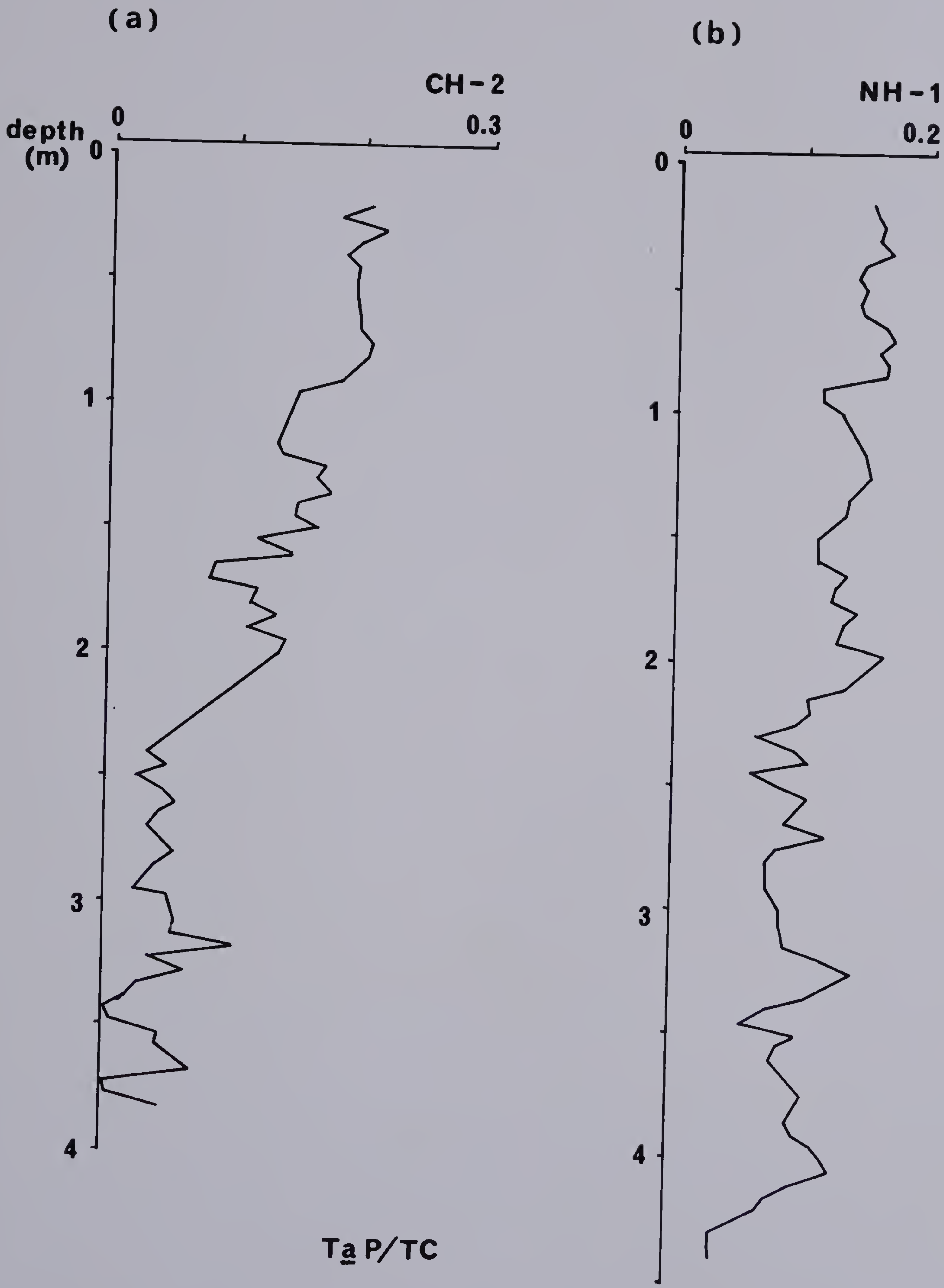
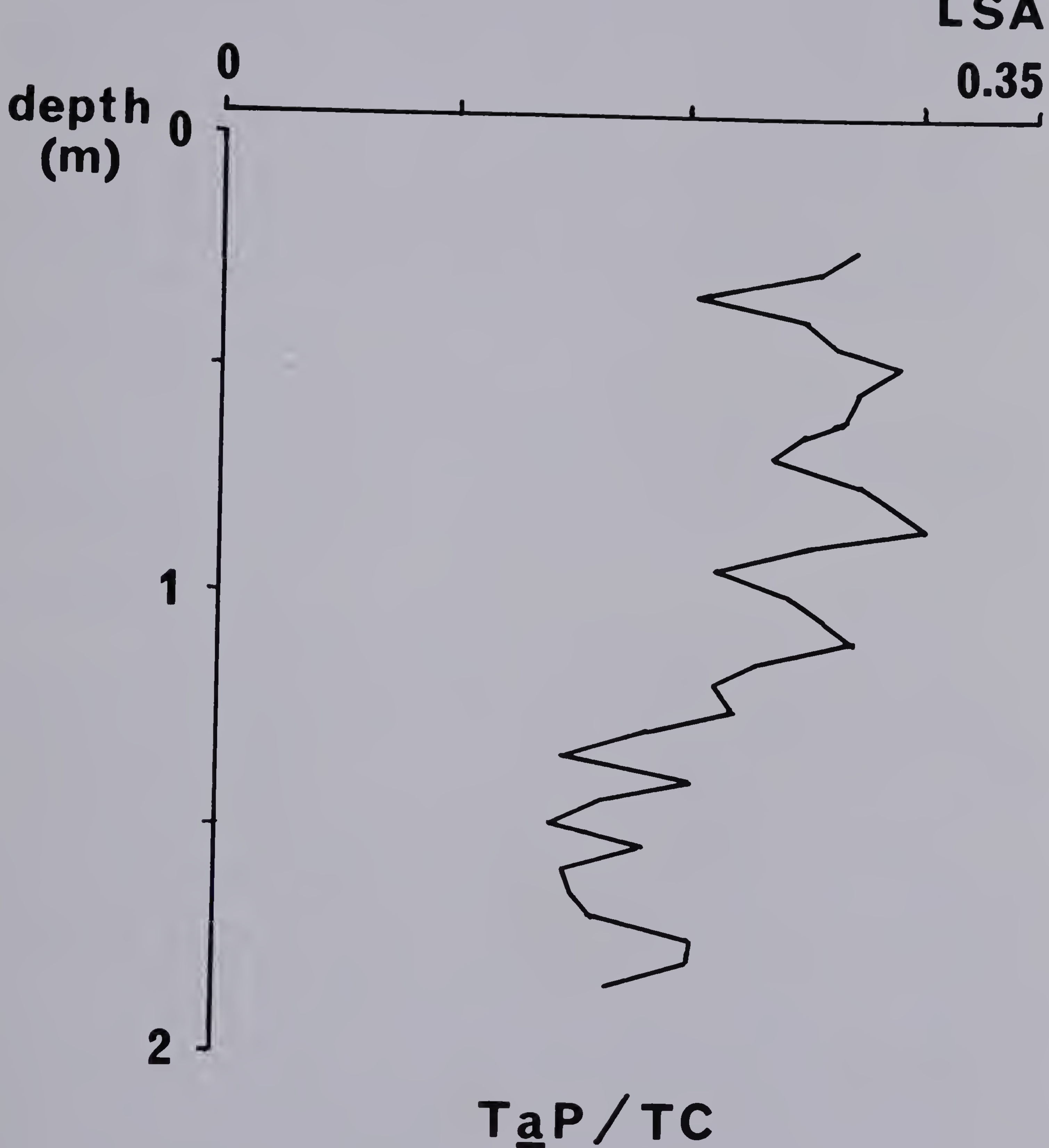

(a)
CH-2
depth (m)
0
0.3
0
1
2
3
4
(b)
NH-1
0
0.2
0
1
2
3
4
Ta P/TC

Figure 28.

Total _a_ pigment : total carotenoid ratios for Lac Ste. Anne.


LSA
0
0.35
depth
(m)
0
1
2
TaP/TC

appears that the central basin of Hastings Lake has been considerably more productive in the latter part of its history, although the extremely low chlorophyll values near the base possibly exaggerate the relative differences between the upper and lower parts. The profile of carotenoids suggests that external contributions in the form of leaf litter and emergent macrophytes may have been much more important early on. The northeast basin has been much more stable, but here too it appears that allochthonous production has increased in importance through time. Both basins have apparently declined in productivity of late.

Lac Ste. Anne has seen little change in production over its history. Here too there is some indication of a greater contribution by macrophytes and leaf litter in its early history.

6. Nutrient levels

Nitrogen and phosphorus in their various forms are the nutrients of most concern for lake productivity. With few exceptions it is phosphorus that is the most critical element in nutrient-limited systems (Schindler 1977). Investigations of nutrient cycling in Manitoba pot-hole lakes (Barica 1974,1977) provide useful insight to systems closely resembling Hastings Lake and Lac Ste. Anne. The pot-holes are similar in being self-contained but dissimilar in suffering from frequent winterkills and summerkills. The latter are a function of the small volume of the lakes, leading to more frequent anoxia. In shallow, self-contained lakes an important source of nutrients is decomposed algal cells. The whole nutrient cycle may thus be closed and independent of external loadings. Although the rapidity of nutrient recycling is promoted by frequent anaerobic conditions, it was shown

that the release of ammonia and phosphate from organic matter occurs during a relative decrease in dissolved oxygen, as well as complete anoxia. Indeed rates of 77 to 79% decomposition of the phytoplankton have been measured in the epilimnion of eutrophic Swiss lakes (Bloesch 1974). Thus while the final levels of refractory phosphorus in closed systems are governed by external loading, the proportion held within the aquatic part of the system is unpredictable. The latter holds for nitrogen as well, but denitrification may result in some overall loss from the system.

Kjeldahl digestion extracts ammonia and organic nitrogen. As the latter is the dominant form of nitrogen in lake sediments, generally comprising 95 to 98% of the total (Bortleson and Lee 1972), TKN should accurately reflect total nitrogen influx to the sediments. Deposition is strongly associated with organic matter (Bortleson and Lee 1972). This is apparent in Hastings Lake, where in both the northeast and main basins there is a strong conformity of the profiles of these components. In both there is little long-term change in the ratio of organic matter to TKN (fig. 26), although in the main basin it is subject to wide short-term fluctuations. These are primarily due to the inclusion of data from both cores in computing the ratios. The nitrogen content of algal remains deposited in sediments tends to be higher than that of organic matter deriving from macrophytes and terrestrial sources (Wetzel 1975). Also the C : N ratio in organic detritus generally increases with the advance of decomposition. If there is a relative decline at any point in the lake's history it suggests that conditions have become less favourable to decomposition (Viner 1977). The failure of the organic matter : TKN ratios to shift in

Hastings Lake, when both the pigment data indicate a change in contributing sources and the Fe : Mn ratios, discussed below, point to changes in preservation conditions, is difficult to explain. It may result from a general decrease through time in nitrogen loading, or from an increase in denitrification.

In Lac Ste. Anne there is a trend towards increasing sedimentary nitrogen throughout the history of the lake, while organic content has remained fairly constant. This results in a decline of the organic matter : TKN ratio through time. This is what one would expect with the shift to the proportionally greater algal production indicated by the pigment data. The increased decomposition suggested by the Fe : Mn ratio in the upper part of the core would tend to shift the organic matter : TKN ratio in the opposite direction.

Phosphorus is commonly co - precipitated with iron under oxidising conditions or with calcium carbonate under fertile conditions. It may also be deposited with undecomposed organic matter (Mackereth 1966, Viner 1977).

In Hastings Lake phosphorus appears to have been deposited primarily in association with calcium carbonate. The peaks and troughs correspond closely with those of calcium, but not at all with iron. However, the considerable increase in precipitation of calcium carbonate in the upper part of CH-2 is not reflected in phosphorus deposition. This implies that the considerable enhancement of productivity at this time did not result from an increase in phosphorus loading. Internal recycling in the system may have improved although there is no evidence for this.

In Lac Ste. Anne the profile of phosphorus corresponds to

none of the elements discussed above with which it may be associated. This implies that there has been a general increase in loading through the lake's history. This has not had any apparent effect on production however, which suggests that the lake is not a phosphorus - limited system.

7. Indicators of water levels

A closed basin such as that of Hastings Lake is extremely sensitive to minor shifts in the balance between precipitation and evaporation. Bozniak and Kennedy (1968) note that spring runoff in 1966 raised the lake level by 2.5cm and heavy June rains by 43.5cm. Over a longer term, a slight increase in mean annual precipitation with a concomitant decrease in evaporation could maintain considerably higher lake levels. A basin such as that of Lac Ste. Anne, which is filled, is much less sensitive to such minor climatic changes. Increased water input will tend to be lost immediately through the outflow. There are a number of indicators that the water in Hastings has undergone radical changes in depth.

The basal date for the northeast basin is 3890 BP. Assuming that this represents the time of initial inundation and that there has been no shift in the relative elevations of the basins, the maximum water depth at CH-1 prior to this must not have been greater than 2.3m.

Oxygen depletion in these lakes occurs primarily during the winter. At this time the decline in turbulent mixing and isolation of the water column from the atmosphere by ice reduces oxygen availability, while the accumulated summer production imposes a considerable oxygen demand. An increase in the relative duration and intensity of reducing conditions would therefore be expected to result from the following: a

climatic shift which lengthened the period of winter ice cover; an increase in organic production which would increase the winter oxygen demand; or a decrease in volume which would limit the oxygen available to meet that demand.

Under oxidising conditions iron and manganese are precipitated as insoluble oxides. If there is a shift to reducing conditions they are remobilized, with manganese being affected first (Mackereth 1966). The greater sensitivity of manganese to the onset of reducing conditions permits the use of the Fe : Mn ratio as an indicator of the oxidation - reduction balance. A decline in the ratio indicates that reduction is less prevalent. The only real difficulty with the procedure is to establish whether an observed change has occurred in the lake itself or in the soils of the basin.

In both the main and northeast basins of Hastings Lake, early Fe : Mn ratios were high and fairly irregular. They later declined sharply and became more stable. The change occurred rather deeper in NH-1 than in CH-2, but chronologically it was probably coincident. In both cases iron influx was greater in the earlier stages. In CH-2 there has been a tendency for manganese to increase with time, whereas, ignoring minor fluctuations, manganese influx to the northeast basin has been stable. If the change in Fe : Mn ratio has resulted from internal events, it indicates a shift to less frequent oxygen depletion in the lake during the latter part of its history. In view of the considerably higher productivity during this period, it suggests a significant rise in lake level. If the decline in the Fe : Mn ratio derives from changes in the watershed, it could imply the same thing. A shift to more reducing soils, deriving from increased precipitation, would free a

relatively greater amount of manganese to enter the lake, causing a drop in the Fe : Mn ratio in the lake sediments. However, the manganese content of a surface sample from the main basin, taken during the autumn when there was no oxygen depletion, was considerably higher than in any of the core samples. The iron content on the other hand was comparable to values obtained in the upper two metres. This suggests that the profiles of the Fe : Mn ratios are indicative of events within the lake rather than outside, with winter reducing conditions removing a portion of manganese oxides accumulated during the summer.

Events in Lac Ste. Anne have caused a somewhat different effect. The high Fe : Mn ratio at the base is attributable to the balance of the two elements in the glacial clay. The rapid decline in the ratio resulted from the onset of reducing conditions in the soils of the drainage basin, as demonstrated in the English lakes (Mackereth 1966). The bulge that occurred in the upper part of the core is of ambiguous origin. The pollen data indicate little vegetation change in the basin, while indicators of lacustrine production also suggest a fairly stable environment. However, the decline at the same time of the organic matter : TKN ratio suggests increased decomposition occurring, which would cause the more intense reducing conditions impied by the higher Fe : Mn ratio.

The shift to a proportionally greater algal contribution indicated by the pigment data in the upper part of CH-2 also suggests a generally higher water level, where littoral processes had less influence. The greater instability of pigments and Fe : Mn ratio profiles near the base imply less stable lake conditions. Short -

term minor fluctuations would have a more profound effect on lake metabolism in shallow conditions than when the water was deeper.

Any increase in water depth must have occurred relatively slowly, otherwise shoreline erosion would have increased the mineral influx to the lake (Hecky 1975). It is of note that sandy inclusions were observed around 2.5m in the cores from the main basin of Hastings Lake. The possession of a small wave and ice moulded bank (Bozniak and Kennedy 1966) reduces the innundation of surrounding land during rising waters and would reduce the effect.

8. Interactions between water depth and productivity

The evidence that there has been a coincidental shift to deeper water and greater productivity in Hastings Lake is of particular interest. The phosphorus data provide no evidence for a concomitant increase in phosphorus loading, so it appears that other factors are controlling production in this system. This is in accord with the findings of Hickman and Jenkerson (1978) who established that light intensity limited phytoplanktonic productivity in Hastings. If this is indeed the case one might postulate two reasons for the apparent coupling of water depth and production. The first is increased volume, that is living space. The second is a reduction in shading by suspended sediments. Non - algal suspended matter, including water colour, is responsible for 48.7% of the light attenuation in Hastings Lake, on average. Neighbouring lakes have similarly high interference. Beaverhill Lake is the highest, having a mean of 71.0% (M. Hickman, unpublished data). This lake has the greatest surface area, the least mean depth, and probably the greatest exposure of any of the lakes for which this characteristic was

determined. One might expect that a rise in water level in one of these non-stratifying lakes would decrease the frequency and intensity of turbulent resuspension of sediments. This would decrease shading by non-algal material and permit enhanced algal production. If this is indeed the case, it would have serious implications for proposals to raise water levels as a measure for habitat improvement.

CONCLUSIONS AND CLIMATIC IMPLICATIONS

The time-span for which historical reconstructions have been made is approximately 4780 years in the main basin of Hastings Lake, 3890 years in the northeast basin, and 5630 years in Lac Ste. Anne.

Pollen analysis suggests that in the earliest part of its history the vegetation around Lac Ste. Anne was more typically parkland and the climate slightly drier. Erosion rates have remained more or less constant, so any climatic shift has not been pronounced.

Productivity within Lac Ste. Anne has changed very little. However, on the basis of the total a pigments to carotenoids ratio, the enhanced carbon to nitrogen ratio, and the relatively high carbonate levels in the lower part of the core, one may tentatively infer that macrophytes made a greater contribution to the total production during the early part of its history.

Changes in Hastings Lake were more pronounced. This is presumably due to its greater sensitivity to subtle shifts in the balance of precipitation and evaporation. Up until approximately 3500 BP the lake appears to have been considerably shallower than since that time. Certainly until 3890 BP, when the northeast basin became part of the lake, the maximum depth in the main basin probably did not exceed 2.5m. This is compared to the present-day maximum depth of approximately 8m. It is of note that a maximum depth of 2.5m would place Hastings Lake in the range of regular or intermittent winter-kill lakes (Barica and Mathias 1979).

During the early shallow-water phase, productivity in general was considerably less than later. Macrophytes probably contributed more

to the total production. Certainly the pigment data suggest that alloch - thonous organic matter, particularly in the form of direct leaf litter fall, contributed significantly to the basal sediments. This is expected as littoral processes and terrestrial events have a stronger impact on lakes of small volume and surface area.

After the rise in water levels, production in Hastings Lake increased and remained fairly steady until about 2500 BP, when a slight decline occurred. Throughout the high water phase oxygen depletion has never been a problem. Any period of reducing conditions in the surface sediments has probably been brief.

The northeast basin also shows evidence for an early unstable phase of shallower water, followed by a very stable history of high production and steady surface elevation. It too shows some diminishing production of late.

The data suggest that productivity in the lakes has never been nutrient - limited. Elevation of the lake surface appears to increase potential volume for production and reduce turbulent resuspension of bottom sediments, permitting greater light penetration and enhanced algal production.

In terms of climatic history, the records correspond to the time following the Hypsithermal Period of warm, dry conditions. It is presumed that as precipitation increased and evaporation decreased, the water table rose and the lake basins filled. This occurred earlier at Lac Ste. Anne, whose closer proximity to the Rocky Mountains subjects it to slightly higher precipitation. The further rise in the level at Hastings Lake at a later period indicates a continued trend to wetter conditions, although the sensitivity of this basin is such that the

change need not have been great.

This record conforms to the vegetational history of east-central Alberta (Lichti-Federovich 1970), where a period of maximum warmth and dryness at about 5500 to 6000 BP was followed by a gradual alteration to wetter and cooler conditions. This was indicated by an increase in boreal elements and a decrease in grassland types. In general, pollen-stratigraphic evidence across the western interior of Canada indicates a southward shift in the boreal forest between 5500 and 2000 BP, which is most easily explained by a shift to a cooler and wetter climate (Ritchie 1976).

Studies of molluscan fauna from southern Alberta also support this interpretation (Harris and Pip 1973), while it is not inconsistent with the record of displacement of the boreal forest-tundra ecotone in Keewatin and Mackenzie (Nichols 1975).

Nevertheless this study has again demonstrated the strongly individual response of lakes, and even basins within lakes, to climatic events.

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APPENDIX A

Notes on Terminology

1. Biological events. In the context of this thesis, this refers specifically to changes in primary productivity and terrestrial vegetation, as indicated by pigment, organic matter, calcium and pollen analyses.

2. Diagenesis. This is applied to the sequence of reactions through which pigments pass upon degradation.

3. Water quality. This term is used here in a restricted sense to denote the chemical makeup of the system. No value judgement is implied or placed upon changes in water quality that are discussed.

APPENDIX B

Chlorophyll diagenesis

As noted in the body of the thesis, chlorophylls degrade to phaeophytins by loss of the magnesium ion; to chlorophyllides by cleavage of the phytol group; and to phaeophorbides by loss of both the magnesium ion and the phytol group. Oxidation of the original chlorophyll yields allomerized chlorophyll, which may then follow the same diagenetic pathways.

The conditions under which these reactions occur are not fully understood, but Brown et al. (1977) have reviewed the experimental evidence available to date. Phaeophytins are formed during cellular lysis by bacterial, viral or autolytic mechanisms, and may also occur in intact algal cells exposed to prolonged darkness. Phaeophorbides have been experimentally produced only through herbivore ingestion and subsequent excretion. Allomers are formed under oxidizing conditions, particularly in the oxidized microzone at the sediment surface. Chlorophyllides have not been formed experimentally, but are presumed to be enzymatically produced.

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